**Cover**

*Aerial view, looking east, of the St. John's city area, showing the harbour, the Narrows and Signal Hill in the background. (Photograph courtesy of Jack Martin, Memorial University of Newfoundland)*

This report is dedicated to Werner Brückner and Stephen Papezik for many memorable field excursions.

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DEPARTMENT OF MINES AND ENERGY
GOVERNMENT OF NEWFOUNDLAND AND LABRADOR

# GEOLOGY OF THE ST. JOHN'S AREA

Arthur F. King

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# CONTENTS

Page

ABSTRACT ........ xiii

INTRODUCTION ........ 1
  LOCATION AND PURPOSE OF STUDY ........ 1
  EARLY GEOLOGICAL STUDIES ........ 1
  PRESENT INVESTIGATION ........ 6

PHYSIOGRAPHY, QUATERNARY GEOLOGY AND GROUNDWATER POTENTIAL OVERVIEW ........ 8
  PHYSICAL SETTING ........ 8
  PREGLACIAL LANDSCAPE ........ 8
  GLACIATION OF THE AVALON PENINSULA ........ 9
  GLACIAL LANDFORMS AND DEPOSITS ........ 10
    Terrain Analysis ........ 10
    Rock and Discontinuous Till ........ 10
    Plain and Veneer Till ........ 11
    Hummocky Till ........ 12
    Lineated Till ........ 12
    Boulder Fields and Erratic Boulders ........ 13
    Terraced Till ........ 14
  ICE MOVEMENT AND DISPERSAL CENTRES ........ 14
  DEGLACIATION ........ 14
  POSTGLACIAL DEPOSITS ........ 15
    Fluvial and Lacustrine Deposits ........ 15
    Organic Deposits and Soils ........ 15
    Mass-Wasting Deposits ........ 15
    Marine Deposits ........ 15
    Land Fill ........ 15
  SURFACE WATER AND GROUNDWATER ........ 16
    Drainage ........ 16
    Water Supply ........ 16
    Water Quantity in Surficial Deposits ........ 16
    Water Quality of Shallow Wells ........ 17
  GROUNDWATER POTENTIAL OF BEDROCK UNITS ........ 17

GEOLOGY OF THE ST. JOHN'S AREA ........ 18
  INTRODUCTION ........ 18
    Regional Geological Setting ........ 18
    Local Geological Setting ........ 19
    Formation Nomenclature and Proposed New Subdivisions ........ 21
  HARBOUR MAIN GROUP (UNITS 1 to 3) ........ 21
    Definition ........ 21
    Local Distribution, Origin, Thickness and Division ........ 24
    St. Phillips Formation (Unit 1) ........ 24
      Name, Distribution and Thickness ........ 24
      Lithology ........ 24
      Structural Relations ........ 24
      Correlation ........ 24
        Beachy Cove Member (Subunit 1a) ........ 24
          Name, Distribution and Lithology ........ 24
          Correlation ........ 24
    Princes Lookout Formation (Unit 2) ........ 25
      Name, Distribution and Thickness ........ 25
      Lithology ........ 25
      Chemistry ........ 25
      Structural Relations ........ 26

Page
Correlation 26
Blast Hole Ponds Unit (Subunit 2a) 26
Portugal Cove Formation (Unit 3) 26
Name, Distribution and Thickness 26
Lithology 26
Structural Relations 28
Correlation and Stratigraphic Implications 28
CONCEPTION GROUP (UNITS 4 and 5) 29
Definition 29
Local Distribution, Thickness and Division 30
Drook Formation (Unit 4) 30
Name, Distribution and Thickness 30
Broad Cove River Member (Subunit 4a) 31
Name, Distribution and Thickness 31
Lithology 31
Structural Relations 31
Correlation 31
Octagon Pond Member (Subunit 4ax) 31
Name, Distribution and Thickness 31
Lithology 31
Structural Relations and Correlation 33
Bauline Line Member (Subunit 4b) 33
Name, Distribution and Thickness 33
Lithology and Structural Relations 33
Correlation 35
Torbay Member (Subunit 4c) 35
Name, Distribution and Thickness 35
Lithology 35
Structural Relations 36
Correlation 36
Mannings Hill Member (Subunit 4d) 36
Name, Distribution and Thickness 36
Lithology 36
Structural Relations 37
Correlation 37
Mistaken Point Formation (Unit 5) 37
Name, Distribution and Thickness 37
Middle Cove Member (Subunit 5a) 39
Name, Distribution and Thickness 39
Lithology 39
Chemistry 40
Structural Relations and Correlation 40
Hibbs Cove Member (Subunit 5b) 41
Name, Distribution, Thickness and Correlation 41
Lithology 42
Contact Relations and Correlation 42
ST. JOHN'S GROUP (UNITS 6 to 8) 42
Definition 42
Local Distribution 42
Trepassey Formation (Unit 6) 43
Name, Distribution and Thickness 43
Lithology 43
Structural Relations 44
Correlation 44
Fermeuse Formation (Unit 7) 44
Name, Distribution and Thickness 44
Lithology 44

Page

- Structural Relations and Correlation 45
- Renews Head Formation (Unit 8) 46
  - Name, Distribution and Thickness 46
  - Lithology 46
  - Structural Relations and Correlation 48
- SIGNAL HILL GROUP (UNITS 9 to 13) 48
  - Definition 48
  - Gibbett Hill Formation (Unit 9) 48
    - Name, Distribution and Thickness 48
    - Lithology 48
    - Contact Relations 50
    - Correlation 50
  - Quidi Vidi Formation (Unit 10) 51
    - Name, Distribution, Thickness and Correlation 51
    - Lithology 52
    - Contact Relations 52
  - Cuckold Formation (Unit 11) 52
    - Name, Distribution and Thickness 52
    - Lithological Subdivisions 52
    - Structural Relations 52
    - Correlation 53
      - Cabot Tower Member (Subunit 11a) 53
        - Name, Distribution and Thickness 53
        - Lithology 53
        - Contact Relations 53
      - Cape Spear Member (Subunit 11b) 53
        - Name, Distribution and Thickness 53
        - Lithology 54
        - Contact Relations 54
      - Skerries Bight Member (Subunit 11c) 54
        - Name, Distribution and Thickness 54
        - Lithology 55
        - Contact Relations 55
  - Blackhead Formation (Unit 12) 55
    - Name, Distribution, Thickness and Correlation 55
      - Petty Harbour Member (Subunit 12a) 58
        - Name, Distribution and Thickness 58
        - Lithology and Contact Relations 58
      - Maddox Cove Member (Subunit 12b) 58
        - Name, Distribution and Thickness 58
        - Lithology 58
        - Contact Relations and Correlation 59
      - Spriggs Point Member (Subunit 12c) 59
        - Name, Distribution and Thickness 59
        - Lithology 59
        - Contact Relations and Correlation 59
      - Deadman's Brook Member (Subunit 12d) 60
        - Name, Distribution and Thickness 60
        - Lithology 60
        - Structural Relations and Mineralization 60
      - Cliff Point Member (Subunit 12e) 60
        - Name, Distribution and Thickness 60
        - Lithology 60
        - Contact Relations 60
  - Flat Rock Cove Formation (Unit 13) 60
    - Name, Distribution and Thickness 60
    - Lithology 61

Page

Knobby Hill Member (Subunit 13a) .......... 61
Name, Distribution and Thickness .......... 61
Lithology .......... 61
Structural Relations, Correlation and Age .......... 61
Piccos Brook Member (Subunit 13b) .......... 62
Name, Distribution and Thickness .......... 62
Lithology .......... 62
Structural Relations and Age .......... 62
DOGBERRY HILL GABBRO (UNIT 14) .......... 63
HOLYROOD INTRUSIVE SUITE (UNIT 15) .......... 63

**PALEOGEOGRAPHIC EVOLUTION** .......... 64
MAJOR PRECAMBRIAN FACIES AND FORMATIONS .......... 64
SUBMARINE MAFIC VOLCANISM .......... 64
The Harbour Main Group .......... 64
SUBMARINE FELSIC PYROCLASTIC ACTIVITY AND BASINAL SEDIMENTATION .......... 64
The Conception Group .......... 64
SHALLOWING UPWARD BASINAL–DELTAIC SEDIMENTATION .......... 67
The St. John's Group .......... 67
FLUVIAL SEDIMENTATION .......... 68
The Signal Hill Group .......... 68
LATE PRECAMBRIAN AND PALEOZOIC MAGMATISM .......... 70
PALEOZOIC SEDIMENTATION .......... 70

**STRUCTURAL GEOLOGY AND METAMORPHISM** .......... 71
REGIONAL STRUCTURAL SETTING .......... 71
TECTONOSTRATIGRAPHIC ZONES .......... 71
Zone I: Topsail Head–Portugal Cove–Bauline .......... 73
Zone II: Princes Lookout–Bauline Line area .......... 73
Zone III: Central St. John's .......... 73
Zone IV: Central to eastern St. John's .......... 73
Zone V: Tor Bay–Downtown St. John's–Mount Pearl–Goulds .......... 73
Zone VI: Eastern Flat Rock–Torbay Point–Petty Harbour–St. John's .......... 73
MAJOR TECTONIC ELEMENTS–DISCUSSION .......... 73
Topsail Fault Zone .......... 73
Kenmount Hill Anticlinorium .......... 74
Lilly Unconformity .......... 74
Flat Rock Thrust Zone .......... 74
Waterford Fault Zone .......... 76
Eastern Deformed Belt .......... 76
MINOR TECTONIC ELEMENTS .......... 76
METAMORPHISM .......... 76
TECTONIC MODELS .......... 77
Synopsis .......... 77

**ACKNOWLEDGMENTS** .......... 78

**REFERENCES** .......... 78

**APPENDIX 1**–Grain-size scale for sediments .......... 87

**APPENDIX 2**–Granulometric classification of pyroclastic and epiclastic deposits (after Schmid, 1981) .......... 87

**APPENDIX 3**–Bedding thickness terms (after Ingram, 1954) .......... 88

# FIGURES

Page

Figure 1: Location and access map of the St. John's study area. The area of study is bounded by the long dashes 2

Figure 2: Geological map of the Avalon Peninsula, 1881 (from Murray and Howley, 1881b)........................ 5

Figure 3: Geological map of the Avalon Peninsula, 1990 (modified after King, 1980, 1982)........................ 7

Figure 4: Surficial landform features of the St. John's study area............................................ back pocke

Figure 5: Simplified geological map of the Avalon Zone in Newfoundland (after King and O'Brien, in press). The index map illustrates the major tectonostratigraphic zones of the Newfoundland Appalachians. 19

Figure 6: Stratigraphic profile of the Upper Precambrian units, eastern Avalon Peninsula (modified after King, 1982) 20

Figure 7: Geological map of the St. John's area. A-B-C transect illustrated in Figure 27........................... 22

Figure 8: Trace-element discriminant diagrams for basalt samples from Princes Lookout Formation, Harbour Main Group. Zr/Y-Zr plot after Pearce and Norry (1979); Ti-Zr-Y diagram after Pearce and Cann (1973); $K_2O+Na_2O-SiO_2$ plot after Irvine and Baragar (1971)............................................ 27

Figure 9: Composite stratigraphic section of the Conception Group.................................................. 30

Figure 10: Geology of Torbay Bight......................................................................................... 32

Figure 11: Geology of the Snagge Point–Middle Cove area, Tor Bay.................................................. 38

Figure 12: Turbidite and hemipelagic subdivision in the upper part of Mannings Hill Member, Paddys Pond Anticline 40

Figure 13: Subaqueous pyroclastic flow unit. Inverse grading in massive lower portion reverts upward to normal grading; alternating fine- to coarse-grained ash beds form the upper portion. Middle Cove Member, Stick Pond.................................................................................................... 41

Figure 14: Composite stratigraphic section of the St. John's Group.................................................... 43

Figure 15: Geological map and sedimentary features of the eastern St. John's study area............................ 49

Figure 16: Composite stratigraphic section of the Signal Hill Group in the type locality............................. 50

Figure 17: Clast and matrix variations in the Cape Spear Member, Cuckold Formation, Cape Spear. (A). Plan view of conglomerate bedding surface showing clasts of rhyolite, tuff, quartz sericite–schist (x), and vein quartz (z) in a poorly sorted matrix. C-axis of largest clast is approximately 4 cm. (B). Grain-size cumulative curve for coarsest stratigraphic level in Cape Spear Member, Sample area 2 $m^2$ by 5 cm thick 55

Figure 18: Geology of the Flat Rock area (after King, 1982)........................................................... 56

Figure 19: Composite stratigraphic section of the Signal Hill Group at Flat Rock Cove.............................. 57

Figure 20: Diagrammatic sections across the Flat Rock Thrust Zone, north of Piccos Brook, Flat Rock Cove (modified after Anderson *et al.*, 1975)........................................................................................ 62

Figure 21: Diagrammatic cross-section through Red Head area showing the Lilly Unconformity and the Flat Rock Thrust Zone (modified after Anderson *et al.*, 1975)................................................................ 63

Figure 22: Late Precambrian and Early Paleozoic development, eastern Avalon Peninsula........................... 65

Page

Figure 23: Submarine fan facies models. A. Original fan model proposed by Walker (1979). B. Generalized hypothetical sequence produced during overall fan progradation. CT = classical turbidites; MS = massive sandstones; PS = pebbly sandstones; CGL = conglomerate; DF = debris flow; SL = slump. Sequences shown by arrows are THIN.-UP (thinning upward) or THICK.-UP (thickening upward) (Walker, 1979) 66

Figure 24: Schematic depositional model for the Lower Conception Group (from Gardiner, 1984)................ 66

Figure 25: Schematic diagram of the St. John's area showing formations and major structures..................... 71

Figure 26: Tectonostratigraphic zones of the St. John's area (see text for explanation)................................ 72

Figure 27: Major structural alignment along the Beachy Cove (A)–Kenmount Hill (B)–Cape Spear (C) transect 75

Figure 28: Distribution of Avalonian–Cadomian–Pan-African terranes in the North Atlantic borderlands (Pre-Mesozoic reconstruction). Az = Avalon Zone, R = Rif, M = Meseta, A = High Atlas, AA = Anti-Atlas, WA = West African Craton, H = Hoggar, EA = East African Craton (King and O'Brien, in press) 77

Map 90-120: Geology of the St. John's area.

# PLATES

Page

Plate 1: Aerial view of the St. John's city area, and showing the Narrows in the background. (Photograph courtesy of Ben Hansen) [illegible]

Plate 2: Alexander Murray, first director of the Geological Survey of Newfoundland [illegible]

Plate 3: Coastal cliffs of Signal Hill, St. John's and Conception groups. Flat Rock Point in foreground, Torbay in background 9

Plate 4: Aerial view of South Side Hills, Petty Harbour area. The flat summit is a remnant of the High Valley Peneplain. Signal Hill Group strata dip steeply eastward 10

Plate 5: Aerial view of eastern Conception Bay with St. Phillips and Broad Cove River in left foreground, St. Thomas in centre and Topsail Head to right 11

Plate 6: Irregular topography in volcanic rocks south of Ore Head, Bauline, the highest elevation (280 m) in the map area 12

Plate 7: Glacial striations and remnants of till ramp-and-crag (i.e., reversed crag-and-till) features on small gabbro stock near Paradise 13

Plate 8: Clast-dominated till (melt-out till) capping matrix-rich gravel (lodgement till), Petty Harbour Road (Goulds) 13

Plate 9: Boulder field, Maddox Cove Road. Freshwater Bay in background 13

Plate 10: Glacial striae, Flat Rock. (Photograph courtesy of Ben Hansen) 14

Plate 11: Frost-shattered till composed of boulders of Hibbs Cove Member (Mistaken Point Formation), Windsor Lake 18

Plate 12: Type locality of Princes Lookout Formation, exposed in fault scarp south of Portugal Cove. Boundary with Drook Formation in upper right 25

Plate 13: Tectonically flattened basaltic pillow lava (Blast Hole Ponds Unit) with individual blocks up to 2 m diameter and 0.5 m in width. Prominent valley defines Ocean Pond Fault and separates unit from Portugal Cove Formation to the west (i.e., upper part of plate) 28

Plate 14: Tightly folded and disrupted volcaniclastic sandstones of Portugal Cove Formation in the type locality 29

Plate 15: Thick, tabular mixtite unit intercalated with volcaniclastic sandstone. Bauline Line Member, Piccos Brook, Flat Rock 34

Plate 16: Pebbly mixtite facies of Bauline Line Member. Felsic volcanic pebbles set in a muddy, sandy matrix, which were injected into fractured clasts. Type locality, Bauline Line 34

Plate 17: Mixtite facies consisting of pebble- to boulder-size clasts set in a muddy sandy matrix, which constitutes about 60 percent of rock sample. Type locality, Bauline Line 34

Plate 18: Streaky-laminated-sandstone facies (facies B-4c) Torbay Member, Thorburn Road 36

Plate 19: Streaky-laminated-sandstone facies of Torbay Member (lower centre) overlain by dark siliceous sandstone and chert of Mannings Hill Member, Torbay 37

Plate 20: Siliceous sandstone and chert of Mannings Hill Member in type locality, opposite Torbay Post Office 39

Plate 21: Parallel- and convolute-laminated siliceous siltstone, tuff and mudstone of the Middle Cove Member, south side of Torbay Bight 42

Page

Plate 22: Slumped and resedimented beds of Fermeuse Formation (facies B-7), east side of Middle Cove....... 45

Plate 23: Problematical markings *Aspidella terranovica* Billings, 1872, interpreted as trace fossil. Fermeuse–Renews Head boundary, Prescott Street, St. John's.......... 45

Plate 24: Lenticular-bedded sandstones and black shale of Renews Head Formation (facies A-8), Outer Cove.. 46

Plate 25: Starved current ripples and pseudo-nodules, Renews Head Formation (facies A-8). Grid divisions are in inches.......... 46

Plate 26: Very thick sandstone units (facies C-8), interbedded with shales and thin sandstones (facies B-8), Renews Head Formation, Outer Cove.......... 47

Plate 27: Thick sheet-sand unit (facies C-8) interbedded with shales and thin sandstones (facies B-8), Renews Head Formation, Northwest Atlantic Fisheries Centre.......... 47

Plate 28: Aerial view of Gibbett Hill, Signal Hill National Historic Park, type section of Gibbett Hill Formation. (Photograph courtesy of Ben Hansen).......... 51

Plate 29: Low-angle planar cross-stratification in Gibbett Hill Formation.......... 51

Plate 30: Type locality of Quidi Vidi Formation (north side of Quidi Vidi Harbour) and Cuckold Formation (Cuckold Head, east of breakwater). (Photograph courtesy of Ben Hansen).......... 51

Plate 31: Thixotropic deformation in Quidi Vidi Formation, Petty Harbour Road.......... 52

Plate 32: Principal reference section of Cabot Tower Member (Cuckold Formation) on north side of Narrows between Cabot Tower and prominent gulch east of North Head. Cape Spear Member occurs to right of gulch and at Fort Amherst Lighthouse (foreground). (Photograph courtesy of Ben Hansen).......... 53

Plate 33: Westward dipping cobble conglomerate of Cape Spear Member, east of Cape Spear lighthouse........ 54

Plate 34: Principal reference section of Cape Spear Member, Logy Bay. Cobble conglomerate forms cliff in foreground. (Photograph courtesy of Ben Hansen).......... 57

Plate 35: Exotic clast of quartz–sericite schist, Cape Spear Member, Cuckold Formation, Logy Bay. Clast maximum diameter 6 cm.......... 57

Plate 36: Red mudstone, siltstone and sandstone (facies A, B, C) of the Maddox Cove Member, Maddox Cove 58

Plate 37: Alternating sandstone and mudstone, cut by sandstone dykes (facies B-12b). Maddox Cove Member, Blackhead Formation.......... 59

Plate 38: Thin section of medium- to very coarse-grained arkosic sandstone (facies A-12c), Spriggs Point Member. Note local concentrations of rock fragments (rhyolite, granophyre).......... 59

Plate 39: Large-scale trough crossbed in Knobby Hill Member, Flat Rock. Paleoflow to south-southwest........ 61

Plate 40: Large-scale planar crossbeds within pebble conglomerate of Knobby Hill Member, Flat Rock Point.. 61

Plate 41: Interfingering of Knobby Hill and Piccos Brook members, Flat Rock Cove.......... 62

# TABLES

Page

Table 1: Stratigraphic nomenclature of the principal formations in the St. John's area as used in this and previous reports ........ 3

Table 2: Hydrogeological characteristics of bedrock units on the Avalon Peninsula including wells within these units in the St. John's area (adapted from Gale *et al.*, 1984, pages 73-79) ........ 17

Table 3: Chemical analyses of basic lavas of the Harbour Main Group, compared with Hawaiite ........ 25

Table 4: Chemical analyses of siliceous volcanic and volcaniclastic rocks, eastern Avalon Peninsula ........ 33

Table 5: Chemical analyses of rock samples from the Fermeuse and Quidi Vidi formations ........ 45

Table 6: Whole-rock trace-element analysis of the bornite−covellite vein, Deadman's Brook Member, Blackhead Formation ........ 60

# ABSTRACT

*Surficial Pleistocene deposits cover about 80 to 85 percent of the St. John's study area. There is a close correlation between type of bedrock and dominant clast-type in till, indicating that the till veneer is of local origin. Postglacial Holocene deposits include organic detritus and alluvium.*

*The most significant geological/geotechnical features, which affect the groundwater movement in the area, are the contrasting hydraulic conductivities of the surficial deposits and the presence of major plunging folds and fracture zones in the underlying bedrock. Tuffaceous siltstones (Mistaken Point Formation), black shales (St. John's Group), and coarse clastics (Signal Hill Group) conformably overlie the generally low-porosity rocks of the Drook Formation, and show moderate to high yields. Iron and manganese, which precipitate along fractures, particularly in the cherts of the Drook Formation and the thin-bedded sandstones of the Renews Head Formation, are known to have an adverse effect on water quality.*

*Upper Precambrian rocks of the St. John's area form the most easterly land exposures of the Avalon Zone in the Appalachian Orogen. The rocks clearly indicate a long history of volcanism, uplift, subsidence and progressive deformation. Fault-bounded pillow basalt and tuff of the Harbour Main Group define the western boundary of the map area. To the east, is a thick marine sequence of volcaniclastic turbidites, debris flows, and argillaceous turbidites of the Conception Group. In the central part of the area, distinctive, waterlain tuffs define the top of the Conception Group, which are conformably overlain by dark-grey shale, discontinuous 'slump' beds of sandstone and grey sandstone of the St. John's Group. The shale–sandstone sequence represents a shoaling of the Conception basin by a turbidite-fronted, southward prograding delta. North of the Avalon Peninsula, green and red sandstones and conglomerates of the Signal Hill Group formed in response to a major uplift and subsequent fluvial deposition. The map area is divided into six main structural zones. The effects of the Acadian deformation appear dominant, but the effects of the late Precambrian Avalonian Orogeny are enigmatic.*

# INTRODUCTION

## LOCATION AND PURPOSE OF STUDY

North America's easternmost city, St. John's (Plate 1), has a rich history of human endeavour and achievement that spans 500 years. Provincial capital, port, and commercial and educational centre, it serves a metropolitan population of about 160,000, including within the map area, the city of Mount Pearl and the towns of Paradise, Goulds, Petty Harbour–Maddox Cove, Portugal Cove, St. Phillips, St. Thomas, Hogan's Pond, Wedgewood Park, Torbay, Logy Bay–Middle Cove–Outer Cove, and Flat Rock (Figure 1). The cities of St. John's and Mount Pearl are rapidly expanding with respect to both residential and commercial development. Mount Pearl's population, for example, numbered 1500 in 1955, then gradually grew to 23,500 in 1988 when it became Newfoundland's third city. The timing, scope, and magnitude of the future expansion of the Port of St. John's and St. John's Airport are subject to such variables as general economic trends, technology, and offshore hydrocarbon resource development.

**Plate 1.** *Aerial view of the St. John's city area, and showing the Narrows in the background. (Photograph courtesy of Ben Hansen)*

Although the Precambrian and Paleozoic rocks of the Avalon Peninsula have been studied for over 100 years, surprisingly, the St. John's area has received only sporadic attention. Little has been published on the Precambrian stratigraphy, particularly of the Harbour Main and Conception groups that comprise approximately two-thirds of the area. The primary objective of this report, therefore, is to document the distribution, origin, and tectonic development of the Precambrian rocks. This survey represents the first systematic, detailed regional mapping and division of the Harbour Main, Conception, St. John's and Signal Hill groups, since they were subdivided in the southern Avalon Peninsula by Williams and King (1979). A secondary objective, is to provide a brief review of published and unpublished reports on the Quaternary geology and groundwater potential, as well as qualitative data on the surficial geology of metropolitan St. John's and surrounding region.

Detailed maps of the Precambrian rocks and tectonic elements, resulting from the field program, should provide an important database for subsequent geological, geotechnical and hydrogeological studies, which are essential for the future development of the region.

## EARLY GEOLOGICAL STUDIES

The first recorded attempt at mining in Newfoundland took place at Shoal Bay, south of Petty Harbour. At about 1773, Alexander Dunn, a St. John's Customs collector, learned of a small copper showing in Shoal Bay and together with two influential friends, John Agnew and George Stewart, applied for and received from King George III, a mining grant. The Shoal Bay mine proved of little value, produced barely enough ore to cover the cost of hiring the team of Cornish miners who worked it, and closed in early 1779 after French sailors kidnapped Alexander Dunn. In 1839, the Shoal Bay site became the property of Captain James Pearl as a reward for his efforts in the Anglo-American naval skirmishes between 1812 and 1830. In 1829, Pearl was granted 1000 acres of land in the western end of the Waterford River valley by the British Colonial Secretary; he died in 1840 but his name is remembered today by the town of Mount Pearl (Malpas and King, 1987).

The appointment of Joseph Beete Jukes in 1839 as 'Geological Surveyor of Newfoundland', marked the beginning of government-sponsored geological and mineral surveys in Newfoundland. The first geological report and map of Newfoundland, produced by Jukes in 1843, provided a description of rocks of the coastal Avalon Peninsula, including a brief account of the main rock types around St. John's. His geological map of Newfoundland shows a belt of 'sienite' and porphyry between Portugal Cove and Cape St. Francis, which is roughly equivalent to the distribution of volcanic rocks of the Harbour Main Group and present in the western part of the map area. His 'Lower Slate Formation', consisting of the lower 'St. John's Slate' unit, and an upper 'Signal Hill Sandstone' unit, is equivalent to that of all the sedimentary units of Precambrian age on more recent maps (Table 1). Jukes (1843) remarked in his report on the potential use of the rocks around St. John's for roofing-slate, and observed that the

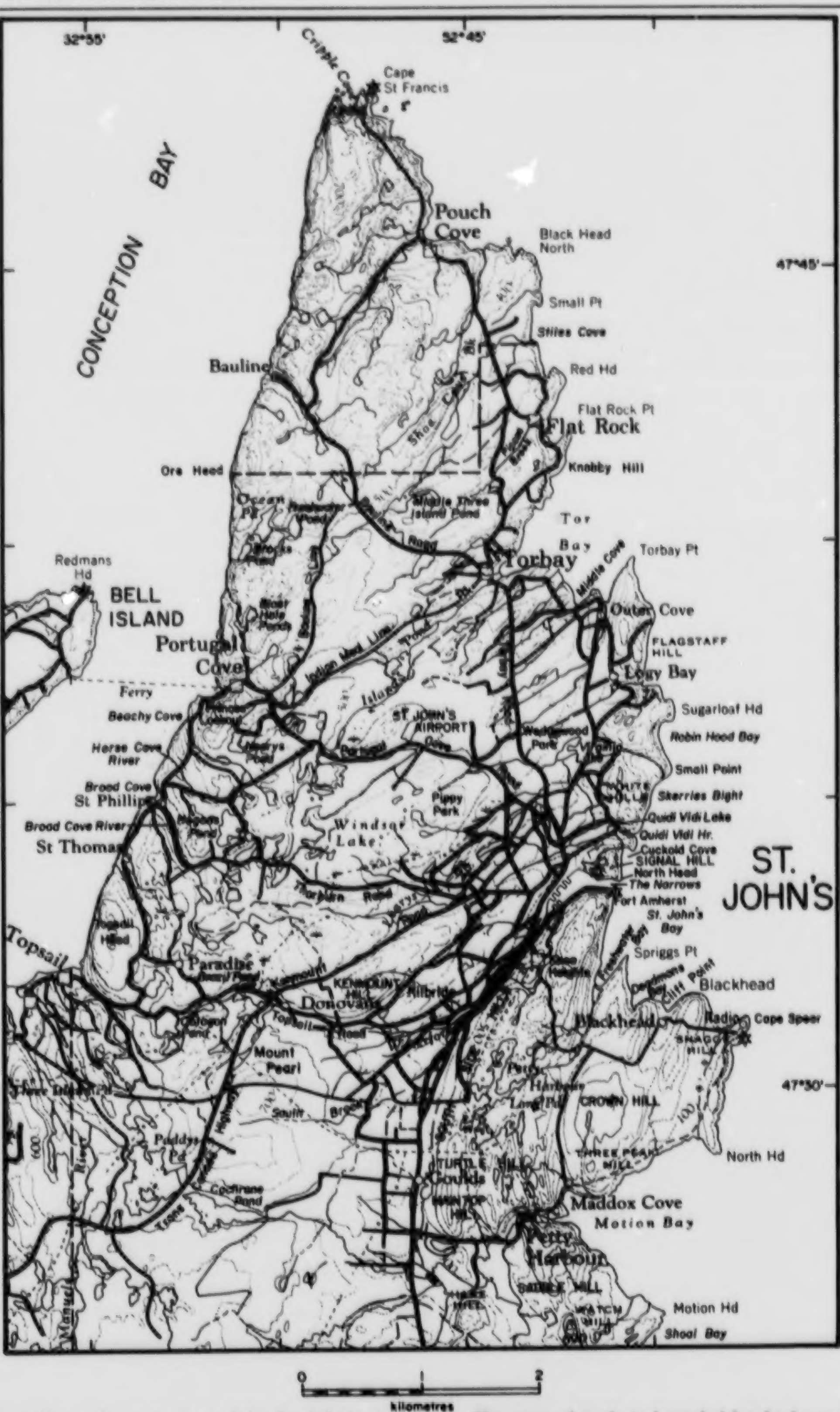

32°55'
52°45'
47°45'
47°30'
Cape St Francis
Cripple Cove
CONCEPTION BAY
Pouch Cove
Black Head North
Small Pt
Stiles Cove
Red Hd
Bauline
Flat Rock Pt
Flat Rock
Ore Head
Knobby Hill
Tor Bay
Torbay Pt
Torbay
Middle Cove
Redmans Hd
BELL ISLAND
Portugal Cove
Outer Cove
FLAGSTAFF HILL
Logy Bay
Ferry
Beachy Cove
Sugarloaf Hd
Robin Hood Bay
ST JOHN'S AIRPORT
Horse Cove River
Small Point
Broad Cove
St Phillips
Skerries Bight
Quidi Vidi Lake
Quidi Vidi Hr.
Broad Cove River
St Thomas
Windsor Lake
Pippy Park
Cuckold Cove
SIGNAL HILL
North Head
The Narrows
Fort Amherst
St. John's Bay
ST. JOHN'S
Spriggs Pt
Topsail
Paradise
Donovans
Kilbride
Blackhead
Cape Spear
Mount Pearl
CROWN HILL
Petty Harbour Long Pd
THREE PEAK HILL
North Hd
Goulds
Maddox Cove
Motion Bay
Petty Harbour
Motion Hd
Shoal Bay
0
1
2
kilometres

**Figure 1.** *Location and access map of the St. John's study area. The area of study is bounded by the long dashes.*

**Table 1.** Stratigraphic nomenclature of the principal formations in the St. John's area as used in this and previous reports

| JUKES 1834 | MURRAY & HOWLEY 1881b | WALCOTT 1899 | ROSE 1952 | | | THIS REPORT AND WILLIAMS & KING 1979 | |
|---|---|---|---|---|---|---|---|
| Signal Hill sandstone | Units f & g: Red sandstone & conglomerate | Signal Hill | CABOT GROUP | Blackhead Formation | | SIGNAL HILL GROUP | Flat Rock Cove and Blackhead Formations |
| | | | | SIGNAL HILL FORMATION | "upper" member | | Cuckold Formation |
| | | | | | "middle" member | | Quidi Vidi Formation |
| | Unit e: Signal Hill grey sandstone | | | | "lower" member | | Gibbett Hill Formation |
| St. John's slate | Unit d: Aspidella Slates | Momable Slate | | St. John's Formation | | ST. JOHN'S GROUP | Renews Head Formation |
| | | | | | | | Fermeuse Formation |
| | | | | | | | Trepassey Formation |
| | Unit c: Auriferous slates & sandstones | Torbay Slate | CONCEPTION GROUP | "Torbay Slate" | | CONCEPTION GROUP | Mistaken Point Formation |
| | | Conception Slate | | "Conception Slate" | | | Drook Formation |
| "Sienite", Porphyry etc. | Units a & b: Metamorphic slates, sandstone, etc. | | HARBOUR MAIN GROUP | | | HARBOUR MAIN GROUP | St. Phillips, Portugal Cove and Princes Lookout Formations |

Signal Hill sandstone and conglomerate 'form admirable materials' for the construction of walls and breakwaters. The red and green fossiliferous 'Variegated Slates' in Trinity Bay, and grey to black 'Belle Isle Shale' of Topsail are equivalent to the formations of Cambrian age established by subsequent workers. The red 'Belle Isle Slate' of Bell Island was rightly described as the relatively youngest sedimentary rock unit on the Avalon Peninsula and is now known to be Early Ordovician. He also observed that the rocks of the Avalon Peninsula were folded 'like corrugations' with the axes of the folds trending north-northeast; his schematic geological cross-section of the structure east of Topsail illustrates the major syncline between Petty Harbour and Cape Spear (Jukes, 1843; Section No. 1). Jukes (1843) also gave a comprehensive account of the physical geography of the Avalon Peninsula. In his report, he notes that around the town of St. John's, many geological features were obscured by 'heaps of drifted and superficial accumulations', and by 'multitudes of boulders', which suggests that he may have been aware of the significance of glacial transport.

The Geological Survey of Newfoundland was established in 1864 and Alexander Murray was appointed its first Director (Plate 2). In 1868, James P. Howley was appointed his assistant, and together they made systematic geological, geographical and topographical surveys of the country until 1883, when Murray retired. Howley succeeded him as director and continued until 1909. The Murray–Howley period was one of continuous economic and scientific studies (Bell, 1892; Hughes, R.D., 1971; Staveley, 1981). The astute descriptions of Murray and Howley respecting agricultural, mineral, and forest wealth of the Island are to be found in the Annual Reports of the Geological Survey of Newfoundland, published between 1864 and 1918 as well as in numerous other publications (e.g. Murray, 1869). These pioneering reports contain much information on the geology of the Avalon Peninsula, including the area of this study. Their geological map of 1881 shows a core of 'Laurentian Gneiss' in the eastern part of the Avalon Peninsula flanked by a concentric arrangement of 'Huronian' slates, sandstones and conglomerates (Figure 2). The 'Laurentian Gneiss' crudely represents the main areas of granitic rocks, now known as the Holyrood Intrusive Suite and their 'Metamorphic Slates and Sandstones etc.' division (Units a & b) corresponds to the volcanic rocks of the Harbour Main Group (Table 1). Their 'Auriferous Slates and Sands' (Unit c) corresponds to the Conception Group, their 'Aspidella slates' (Unit d) to the St. John's Group, and their overlying 'Signal Hill grey sandstone, red sandstone and, conglomerate' (Units e, f, and g) to the Gibbett Hill, Quidi Vidi, Cuckold and Blackhead formations of the present Signal Hill Group.

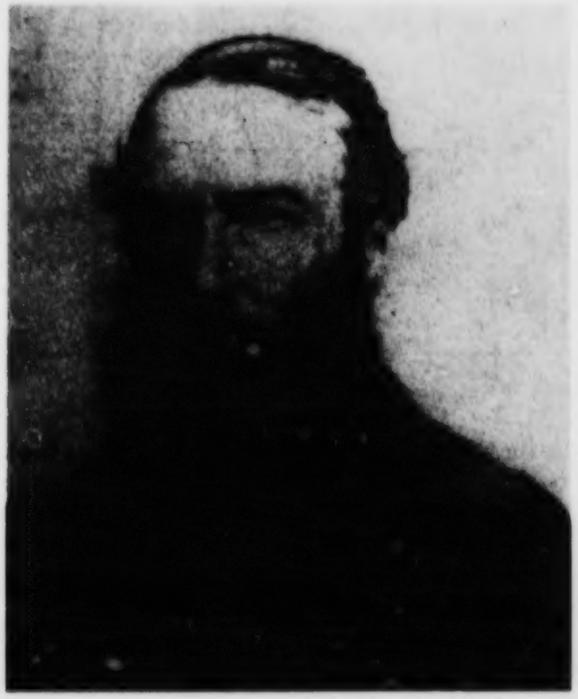


**Plate 2.** *Alexander Murray, first director of the Geological Survey of Newfoundland.*

Walcott (1899) proposed the name 'Avalon Terrane' for the Precambrian sedimentary rocks lying above the 'Archean gneisses' (roughly corresponding to the present Harbour Main Group). As shown in Table 1, he substituted the names 'Conception Slate' and 'Torbay Slate' for the 'Auriferous slates' of Murray and Howley (1881a), renamed their 'Aspidella slates' as 'Momable' and retained the name 'Signal Hill' for the coarse clastic formations comprising the upper part of this 'terrane'. Walcott (1900) subsequently introduced the term 'Random Terrane' for strata lying between the Signal Hill conglomerate and overlying Cambrian beds in the Trinity Bay area.

In 1907, J.P. Howley published a coloured map, which delineated the major geological formations of Newfoundland and indicated the locations of major sources of minerals. He recognized on the Avalon Peninsula a series of 'mixed igneous and aqueous deposits of lower Huronian age', corresponding, in part, to Murray and Howley's (1881a) 'Laurentian Gneiss' and including the 'Metamorphic Slates and Sandstones etc.' division. The sedimentary rocks lying between the Huronian and Cambrian formations were provisionally termed 'Avalonian' after Walcott's (1899) 'Avalon Terrane'.

A.F. Buddington, a member of the Princeton expeditions to Newfoundland in 1913-1914, described the petrology of the Precambrian granitoid and volcanic rocks occurring in the eastern part of the Avalon Peninsula (Buddington, 1916, 1919). Buddington (1919) correctly recognized that the 'Laurentian Gneiss' was mainly upper Precambrian granite, which he called the 'Holyrood Granite batholith'. He proposed the name 'Avondale Volcanics' for the rocks corresponding to Howley's (1907) 'Lower Huronian series of mixed igneous and aqueous deposits'. Buddington (1919) suggested that the 'Avalonian' sedimentary series was derived directly or indirectly from rocks of volcanic origin. He supported the observations of Murray and Howley (1881a) on the resemblance of the Avalonian sedimentary series to the gold-bearing or 'Auriferous series' of Nova Scotia; he states (Buddington, 1919, p. 469): '...the Goldenville quartzites present certain resemblances to the Conception Slate series, the banded argillite division ... to the Torbay series, and the Halifax formation to the Momable series.' The Goldenville and Halifax formations, as they are now known, are included in the Cambro-Ordovician Meguma Group, of southern mainland Nova Scotia.

The early geological studies of the Avalon Peninsula (in the pre-Confederation era), were of either a broad reconnaissance or a local detailed nature. Regional geological relationships were poorly understood, and a mapping program was therefore designed that would eventually lead to the production of detailed maps of most of the Avalon Peninsula. Rose (1952) commenced this program in 1948 for the Geological Survey of Newfoundland, and continued it, in 1949, for the Geological Survey of Canada (GSC). The GSC maps and reports of Rose (1952), Hutchinson (1953), McCartney (1967) and Williams and King (1979) are the standard references on the regional geology of the Avalon Peninsula. Rose (1952) redefined the Precambrian rocks within the Torbay map area (Table 1) and produced the first detailed geological map of the region, at 1:253,440 scale. He

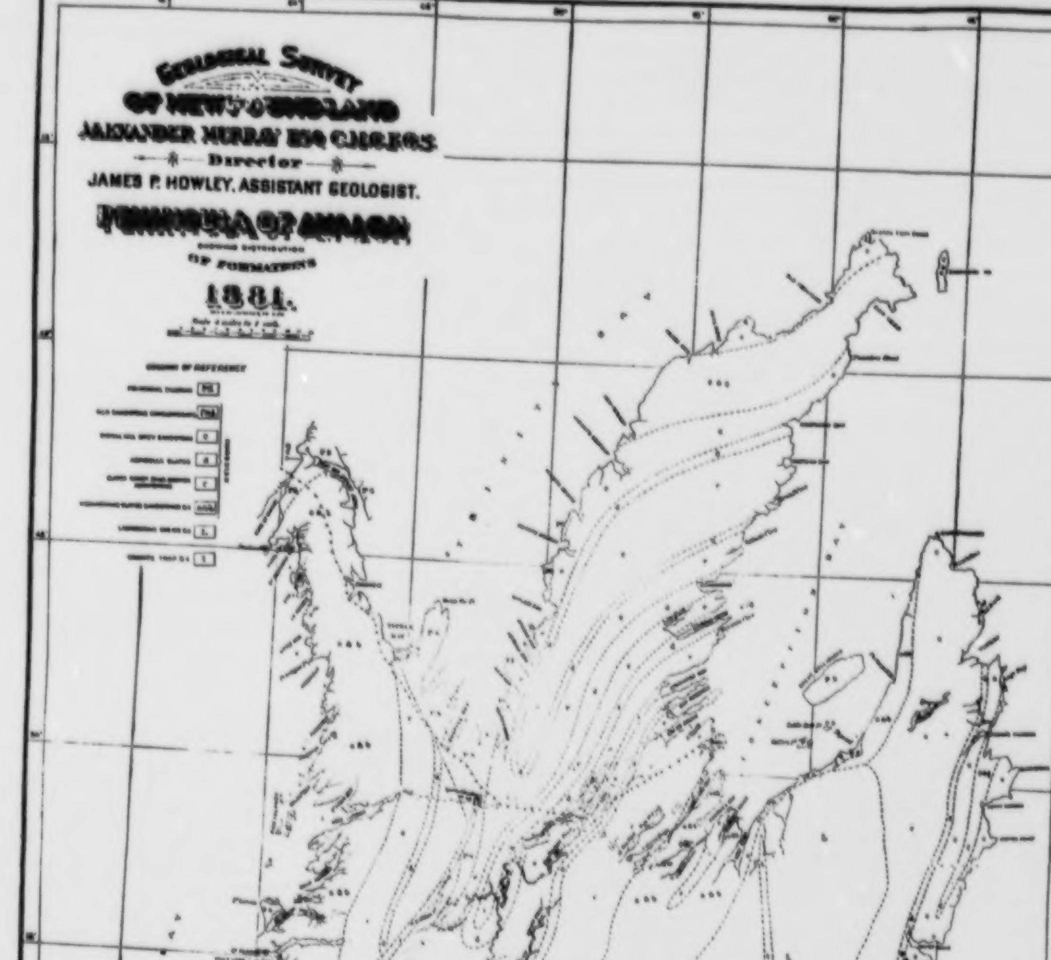

Geological Survey
of Newfoundland
Alexander Murray Esq. C.M.G. F.G.S.
Director
James P. Howley, Assistant Geologist.
Peninsula of Avalon
showing distribution
of formations
1881.

**Figure 2.** *Geological map of the Avalon Peninsula, 1881 (from Murray and Howley, 1881b).*

introduced the name 'Harbour Main Group', for the volcanic and associated minor sedimentary rocks previously termed the 'Avondale Volcanics' by Buddington (1919) and 'Harbour Main Volcanics' by Howell (1925). The 'Conception Slate' and 'Torbay Slate' were informally retained within his 'Conception Group'. Rose (1952) introduced the name 'Cabot Group' to include three conformable sedimentary formations, which, in ascending order are the St. John's, Signal Hill, and Blackhead formations. Williams and King (1979) in their studies of the Trepassey map area, southern Avalon Peninsula, divided the Conception Group into five formations (Figure 3). They elevated both the St. John's and Signal Hill formations to group status, subdivided them into formations, and abandoned the name Cabot Group (Table 1).

The only other published large-scale geological map, specifically of the St. John's area, is that of Hsu (1975) at 1:50,000 scale. Hsu (1975) divided the Harbour Main Group between Topsail and Cape St. Francis into three lithological divisions, and the Conception Group in the Torbay–Shoe Cove area into two lithological divisions; the Conception Group south of a line between Portugal Cove and Virginia Lake was undivided. Both the St. John's and Signal Hill groups were informally divided into formations and their general distribution shown.

Geological studies with reference to the petrology, sedimentology, paleontology and structural aspects of the St. John's area include publications by Brückner, (1969a), Hughes (1970, 1976), Hughes and Brückner (1971), King (1972a, b, 1980, 1982, 1984, 1986, 1988), King *et al.* (1974), Anderson (1972), Anderson *et al.* (1975), Papezik (1972a, b, 1973, 1974a, b), Hsu (1976), Hofmann *et al.* (1979), Anderson and King (1981), Anderson and Conway Morris (1982), and O'Brien *et al.* (1983).

Unpublished theses (M.Sc.) include the work of Singh (1969), who carried out a petrological study of the Signal Hill Group, and of Hsu (1972), who described the sedimentology of the St. John's Group. Unpublished dissertations (Honours) by a number of Memorial University of Newfoundland geology students include general mapping of selected areas around St. John's between 1962 and 1972.

The surficial geology and geomorphology of parts of the central and eastern Avalon Peninsula have been described by MacClintock and Twenhofel (1940), Brückner (1969b, 1979), Henderson (1972), Nolan *et al.* (1972), Rhodenizer (1972), Rogerson and Tucker (1972), Rogerson (1974, 1982), Vanderveer (1975), Tucker (1976), Heringa (1981), Macpherson (1982, 1985), Batterson (1984), and Gale *et al.* (1984). The reports and maps of Henderson (1972), Vanderveer (1975), Macpherson (1982, 1985), Batterson (1984), and Gale *et al.* (1984) are the major sources of information used in the following chapter of this report as part of an overview of Quaternary geology and groundwater potential.

## PRESENT INVESTIGATION

Mapping of the bedrock geology and surficial deposits of 500 km², in and around St. John's, at 1:12,500 scale was undertaken during 1985-1986, under contract with the Geological Survey Branch of the Newfoundland Department of Mines and Energy. The contract area, shown in Figure 1, bounded by north latitudes 47°27' and 47°40', and west longitudes 52°37' and 52°53' ('the map area'), comprises eleven Newfoundland Department of Forest Resources and Lands 1:12,500 map sheets (0252; 0253; 0255; 0256; 0259; 1251; 1254; north half of 0258 and 1257; south half of 0288 and 0289), and eight NTS 1:25,000 map sheets (IN/10c; IN/10b,a; north half of IN/7f and IN/7g; south half of IN/10f and IN/10g; east half of IN/10d and IN/7e). Survey station and monument co-ordinates cited in this report are shown on the 1:12,500 scale map sheets.

Surficial sediments were examined in order to provide insight into mapping and interpreting bedrock geology in areas of little or no rock exposure. Particular attention was paid to the lithology and texture of till clasts. About 5 site descriptions per km² were made and data were plotted on 1:12,500-scale maps. It was found that there is a close correlation between type of bedrock and dominant clast-type in till, indicating that the till veneer is of local origin and commonly less than one kilometre from source. Comparable transport distances (1 to 2 km) were earlier suggested by Batterson (1984, p. 17) for tills in the Waterford River valley.

The coastal geology was investigated in some detail and inland traverses were run from roads and rivers and along tracks, trails, and transmission lines. Quarries, trenches, and water-sewer lines and various other excavations were examined and sampled. A helicopter was used to map the inaccessible coastal cliffs north of Portugal Cove and south of Torbay Point. A canoe was used on ponds and lakes. Colour aerial photographs (1:12,500 scale) were useful in defining lithological and surficial landform boundaries. Black and white aerial photographs, taken in the mid-1940's, were particularly useful in determining structural trends in former areas of bedrock that are now industrial or housing estates. Initial maps were plotted at a scale of 1:12,500 and at 1:5,000 for the Torbay–Outer Cove area. (These are available for inspection at the Newfoundland Department of Mines and Energy). In total, approximately 1700 site descriptions of bedrock and surficial deposits were made. A summary of the main bedrock geological features presented in this report is incorporated in a new geological map of the Avalon Peninsula compiled by King (1988).

Stratigraphic sections were measured at Flat Rock, Torbay, Middle Cove, Outer Cove, Torbay Point, Logy Bay, Quidi Vidi Harbour, St. John's Narrows, Petty Harbour and Cape Spear. These sections enable construction of a regional stratigraphic profile and are of value in interpreting depositional processes and paleoenvironments. As part of the sedimentological study, special attention was paid to clast composition, clast size and shape (Appendix 1), clast composition (see Appendix 2) and bed thickness (see Appendix 3). Sand–silt grains were measured by means of a visual size–shape comparator and an optical (8x) micrometer. Maximum particle size was determined for mixtites and conglomerates because it will give, for some

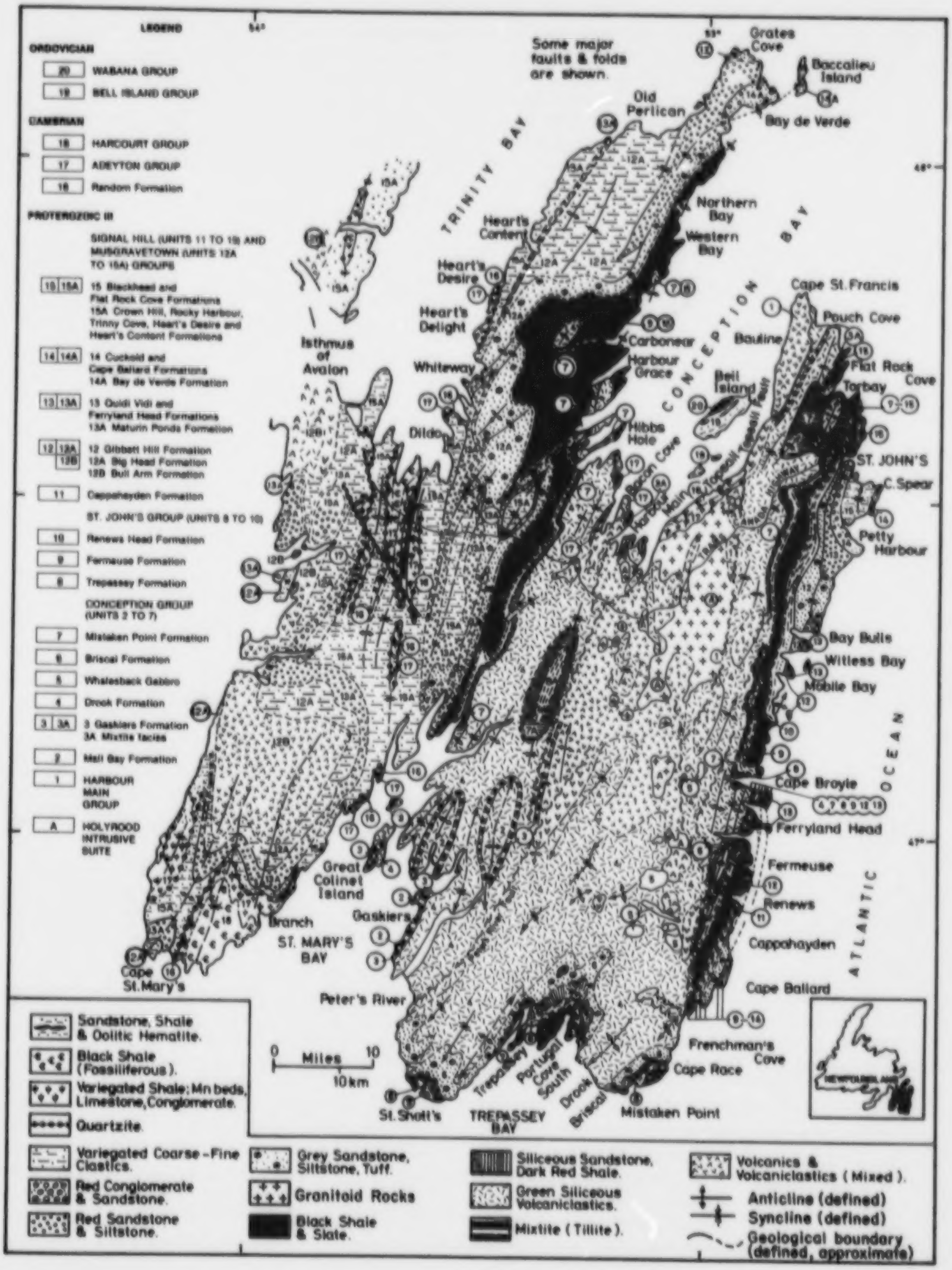

LEGEND
ORDOVICIAN
20 WABANA GROUP
19 BELL ISLAND GROUP
CAMBRIAN
18 HARCOURT GROUP
17 ADEYTON GROUP
16 Random Formation
PROTEROZOIC III
SIGNAL HILL (UNITS 11 TO 15) AND MUSGRAVETOWN (UNITS 12A TO 15A) GROUPS
15 15A 15 Blackhead and Flat Rock Cove Formations 15A Crown Hill, Rocky Harbour, Trinny Cove, Heart's Desire and Heart's Content Formations
14 14A 14 Cuckold and Cape Ballard Formations 14A Bay de Verde Formation
13 13A 13 Quidi Vidi and Ferryland Head Formations 13A Maturin Ponds Formation
12 12A 12B 12 Gibbett Hill Formation 12A Big Head Formation 12B Bull Arm Formation
11 Cappahayden Formation
ST. JOHN'S GROUP (UNITS 8 TO 10)
10 Renews Head Formation
9 Fermeuse Formation
8 Trepassey Formation
CONCEPTION GROUP (UNITS 2 TO 7)
7 Mistaken Point Formation
6 Briscal Formation
5 Whalesback Gabbro
4 Drook Formation
3 3A 3 Gaskiers Formation 3A Mixtite facies
2 Mall Bay Formation
1 HARBOUR MAIN GROUP
A HOLYROOD INTRUSIVE SUITE
54°
53°
48°
47°
Some major faults & folds are shown.
Grates Cove
Baccalieu Island
Bay de Verde
Old Perlican
TRINITY BAY
Heart's Content
Northern Bay
Western Bay
CONCEPTION BAY
Heart's Desire
Heart's Delight
Cape St. Francis
Pouch Cove
Carbonear
Harbour Grace
Bauline
Isthmus of Avalon
Whiteway
Flat Rock Cove
Bell Island
Torbay
Dildo
Hibbs Hole
ST. JOHN'S
C. Spear
Petty Harbour
Bay Bulls
Witless Bay
Mobile Bay
Cape Broyle
Ferryland Head
Fermeuse
Renews
Cappahayden
Cape Ballard
ATLANTIC OCEAN
Great Colinet Island
Gaskiers
Branch
ST. MARY'S BAY
Cape St. Mary's
Peter's River
Frenchman's Cove
Cape Race
Mistaken Point
St. Shott's
TREPASSEY BAY
Trepassey
Portugal Cove South
Drook
Briscal
0 Miles 10
10 km
Sandstone, Shale & Oolitic Hematite.
Black Shale (Fossiliferous).
Variegated Shale; Mn beds, Limestone, Conglomerate.
Quartzite.
Variegated Coarse-Fine Clastics.
Red Conglomerate & Sandstone.
Red Sandstone & Siltstone.
Grey Sandstone, Siltstone, Tuff.
Granitoid Rocks
Black Shale & Slate.
Siliceous Sandstone, Dark Red Shale.
Green Siliceous Volcaniclastics.
Mixtite (Tillite).
Volcanics & Volcaniclastics (Mixed).
Anticline (defined)
Syncline (defined)
Geological boundary (defined, approximate)

**Figure 3.** *Geological map of the Avalon Peninsula, 1990 (modified after King, 1980, 1982).*

processes, a numerical approximation of the minimum competence of the gravel-transporting currents (see Bluck, 1964; Steele, 1974, p. 338). In many areas, the rock is poorly indurated and it is possible to remove pebbles and cobbles and to measure their long, intermediate and short axes; approximately 200 samples of clasts and matrix were collected for subsequent laboratory study. Colour slides of plan and profile views of beds were projected on a Shadowmaster and drawings made of textures (e.g., see Figure 17). Directional current structures present in sandstones and conglomerates were classified by size and type (e.g., Allen, 1963, 1964, 1966, 1982; High and Picard, 1974). Most readings were taken on large-scale trough crossbeds in areas of low tectonic dip. Vector mean and magnitude were calculated by the methods of Curray (1956) and Miall (1974, 1985). The nature of most rock exposures restricted determination of possible ancient channel sinuosity (e.g., Moody-Stuart, 1966; Miall, 1985).

# PHYSIOGRAPHY, QUATERNARY GEOLOGY AND GROUNDWATER POTENTIAL OVERVIEW

## PHYSICAL SETTING

A combination of both lithology and structural style controls the physiography of the study area. The most striking physiographic features are the north-northeast-trending hills, on both the eastern and western sides of the map area, exposing virtually continuous rock sections along steep slopes and rugged shorelines. Weather resistant beds of arkosic sandstone and conglomerate form the salient coastal cliffs between Flat Rock Point (Plate 3) and Knobby Hill, 137 m above sea level (a.s.l.), and the prominent range of hills between Torbay Point and Petty Harbour. The latter includes (from north to south) Flagstaff Hill (191 m), White Hills (160 m), Signal Hill (154 m), South Side Hills (239 m), Turtle Hill (214 m), Maintop Hill (226 m) and Saddle Hill (213 m). The conglomerate beds between Torbay Point and Petty Harbour (Plate 4) dip steeply eastward, extend under St. John's and Motion bays, and reappear at Cape Spear National Historic Park, where they can be seen as gently westward dipping beds, forming a 5-km-long ridge of steep sea cliffs, with peaks up to 93 m a.s.l.

The gently undulating central part of the region and the low-lying area between St. John's and Motion bays are generally smooth due to glacial action. These two areas are characterized by extensive surficial and bog deposits and only minor exposures of rock away from the coast; dense thickets of spruce and fir are common and the terrain is difficult to traverse on foot. Soft shales form the low-lying area between Outer Cove and the Goulds. West of the shales, hard weather-resistant siliceous beds form prominent knobs and ridges; the highest peaks are Kenmount Hill (261 m), the hills south of Mount Pearl (240 m), the hills near Big Pond, Pippy Park (224 m) and the Tolt Hills (210 m).

The high, coastal range between Bauline and Topsail Head (Plate 5) is underlain by volcanic and volcaniclastic rocks. This range, in contrast with the Torbay Point–Petty Harbour range to the east, is characterized by irregular and rough topography, reflecting the lithological and structural complexities of the region; peaks are generally 130 to 200 m a.s.l., but at Ore Head, south of Bauline, the coast rises sheer to about 280 m, the highest elevation in the map area (Plate 6).

## PREGLACIAL LANDSCAPE

Geological events in eastern Newfoundland are recorded mainly in rocks of Late Precambrian and Early Paleozoic age. Rocks of Cambrian and Ordovician age, in the Conception Bay and in the adjacent offshore region (e.g., King *et al.*, 1986; King, 1988), were once more widely distributed across the Avalon Peninsula than now, but together with any younger strata that may have been deposited above them, have since been eroded away. The submarine rock record, east of the Avalon Peninsula, indicates marine conditions during the Mesozoic and Early Cenozoic, but most of the area was probably above sea level during this period.

MacClintock and Twenhofel (1940) suggested that the upland erosion surfaces of the Avalon Peninsula are remnants of the older, much-dissected High Valley Peneplain and the Lawrence peneplain, both of which appear in western and central Newfoundland. They correlated the Lawrence peneplain with the extensive upland surfaces of gently rolling topography between 100 and 200 m a.s.l. that makes up most of the Avalon Peninsula. The High Valley Peneplain is represented on the Avalon Peninsula by uplands and by separate hills or ridges 200- to 300-m high.

The preglacial landscape of the St. John's area evolved over a long period of time under varying climates. The flat summits of the South Side Hills (Plate 4) and the high coastal rim south of Bauline (Plate 6) are remnants of the High Valley Peneplain (Henderson, 1972, p. 7, 8) and probably developed before the whole relief had been modified by Pleistocene glaciation. Glaciation has not greatly altered the surface morphology of the larger bedrock landforms (Henderson, 1972, p. 5). A lower, flattish topography, well exposed between Torbay and St. John's Airport (elev. 135 m) may have developed during a younger, though preglacial period of erosional planation (Brückner, 1979, p. 6); the undulating topography between St. John's and Motion bays with peaks up to 185 m a.s.l. may also have developed at the same time. Preglacial drainage patterns may have shown a greater degree of structural control with streams following fault-bounded valleys and steeply-dipping strata along the coast. In the interior, smaller streams probably flowed outward from structural domes and inwards in the case of structural basins.

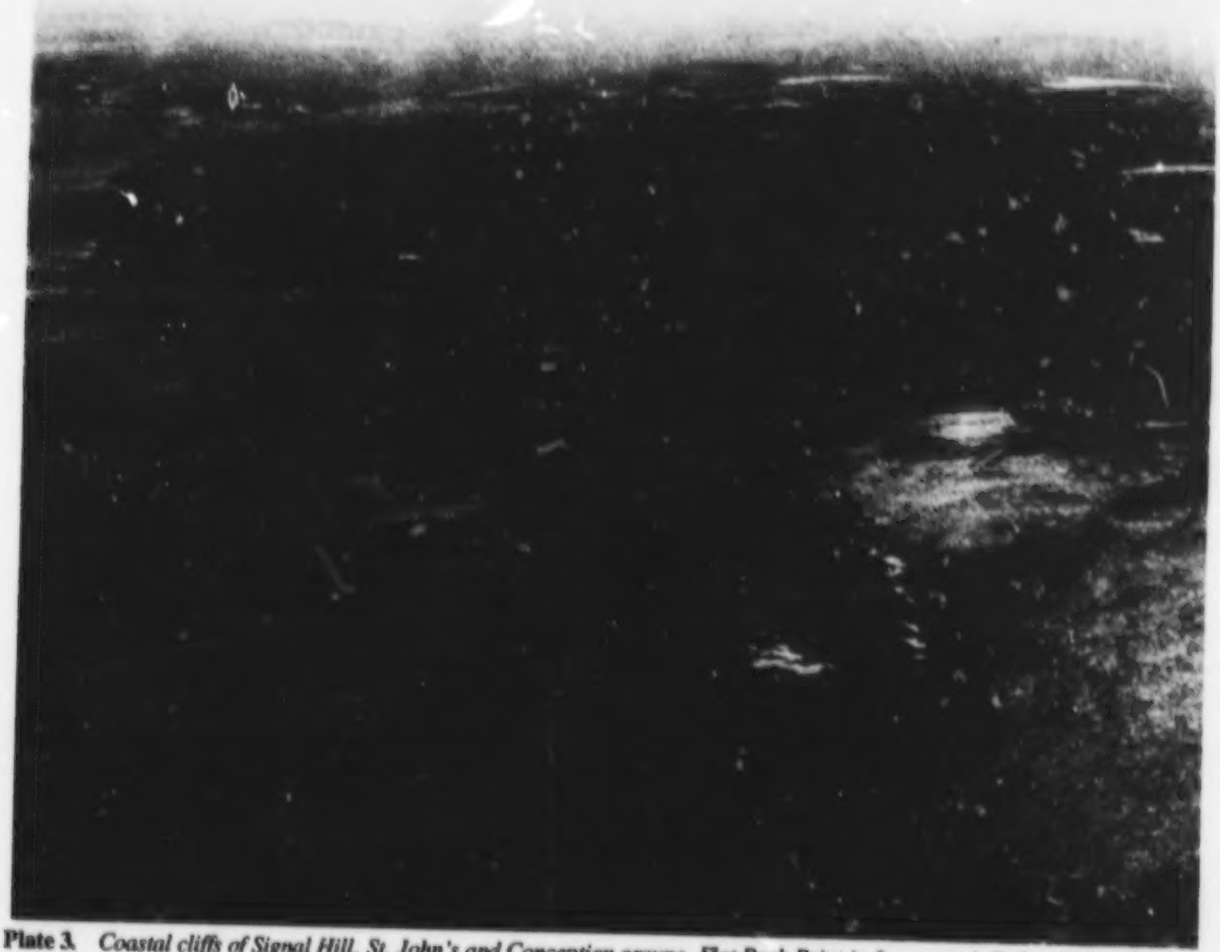


**Plate 3.** *Coastal cliffs of Signal Hill, St. John's and Conception groups. Flat Rock Point in foreground, Torbay in background.*

## GLACIATION OF THE AVALON PENINSULA

During the Pleistocene, the Avalon Peninsula was glaciated, perhaps repeatedly, although no substantial evidence of pre-Wisconsinan glaciation has been documented (Rogerson, 1982; Gale *et al.*, 1984). The concept that during the Wisconsinan, the Avalon Peninsula was covered by an ice cap extending from the main part of the island (MacClintock and Twenhofel, 1940) has not been supported. In contrast, Summers (1949) and Henderson (1972) suggested that the Avalon Peninsula had its own ice cap. Henderson (1972, p. 19) concluded that at the Wisconsinan glacial maximum, the Avalon ice cap formed a dome over the head of St. Mary's Bay and radiated outward in all directions; ice divides subsequently developed at the centre of the Bay de Verde and St. John's peninsulas, with ice drainage down the slope of the land to the coast (Rose, 1952; Henderson, 1972). Ice over the St. John's region was thin (probably less than 700 m) and possibly local, but confluent with the main ice cap (Batterson, 1984). The margin of the ice sheet was probably close to the present coastline (Rogerson, 1974; King *et al.*, 1986).

**Plate 4.** *Aerial view of South Side Hills, Petty Harbour area. The flat summit is a remnant of the High Valley Peneplain. Signal Hill Group strata dip steeply eastward.*

# GLACIAL LANDFORMS AND DEPOSITS

## Terrain Analysis

The general distribution of Pleistocene and Recent surficial deposits within the Avalon Peninsula is discussed in a significant report by Henderson (1972). Major surficial landforms and ice-flow features are shown on his map of the Avalon at 1:250,000 scale. A detailed aerial photograph analysis of the terrain features was used by Vanderveer (1975) to develop a surficial landform classification and terrain map (1:50,000 scale) of the St. John's area. A similar approach was used by Batterson (1984) to produce a terrain map (1:15,000 scale) of the Waterford River basin.

Field observations of surficial features confirm and supplement the terrain analysis of previous workers. A simplified summary of terrain units within the map area (after Henderson, 1972; Vanderveer, 1975; Batterson, 1984), including modifications and additional data on ice-flow indicators, such as glacial striae, grooves, roches moutonnées, crag-and-tail and erratic boulder provenance, is shown in Figure 4 (back pocket). The following account reviews the characteristics of the main landform units.

## Rock and Discontinuous Till

About 85 percent of the map area is covered by till and various other minor surficial deposits. The remainder consists primarily of ridges and knobs of rock outcrop that may, in part, be overlain by a thin (1 to 3 m), discontinuous veneer of till or vegetation. This landform unit typically forms high ground or coastal cliffs, and the bedrock commonly shows glacial striae, grooves and roches moutonnées.

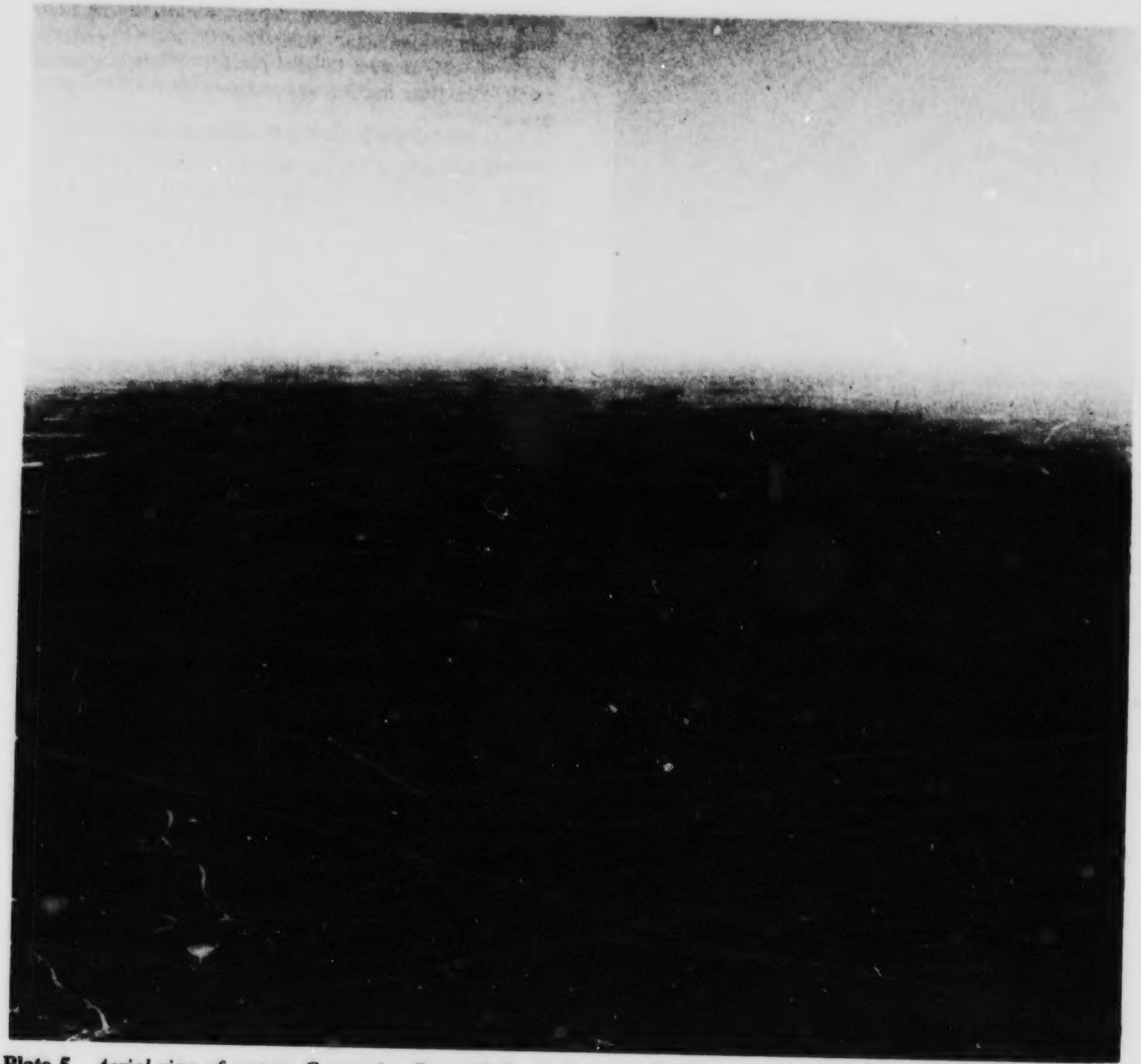


**Plate 5.** *Aerial view of eastern Conception Bay with St. Phillips and Broad Cove River in left foreground, St. Thomas in centre and Topsail Head to right.*

## Plain and Veneer Till

Henderson (1972) observed that in general, the effect of till cover on the Avalon Peninsula is to smooth the surface relief by filling small bedrock valleys and depressions. This observation was substantiated by Rhodenizer (1972), Batterson (1984) and by the writer during field investigations.

In the low-lying central part of the map area (Figure 4), most of the bedrock is overlain by a continuous veneer of till. The veneer deposits are generally less than 3 m thick with features of the underlying rock usually evident. Plain till deposits are greater than 3 m thick and mask all bedrock features. They generally fill elongated depressions in the underlying topography. The veneer till deposits are locally eroded and dissected as are the thicker tills, particularly along river channels.

The City of St. John's is covered by a relatively thin layer of till (Henderson, 1959). In a detailed compilation and assessment of drill-hole and seismic data, Rhodenizer (1972) demonstrated by means of an isopach map (1:6,000 scale) that approximately 90 percent of the City of St. John's has less than 3 m of overburden with the thickest concentrations (5 to 6 m) located in river valleys, ponds and drift-filled ancient river valleys. Batterson's (1984) isopach map of the Waterford

**Plate 6.** *Irregular topography in volcanic rocks south of Ore Head, Bauline, the highest elevation (280 m) in the map area.*

River basin shows the thickest recorded till depths in the City of Mount Pearl of up to 4.5 m along the Waterford River near Donovans.

The plain and veneer tills are very compact, poorly sorted and matrix-rich. They are composed of variable amounts of clasts (35 to 70 percent), sand (15 to 30 percent) and silt–clay (generally around 25 percent but with low clay values). Pebble- to cobble-size clasts are common; most are angular to sub-rounded and are locally derived. Locally, large, sub-angular blocks of rock and sub-rounded boulders occur, some of which are striated; most of these clasts are also locally derived.

The composition, hardness and structural geometry of the source rock strongly influence the size and shape of the clasts. For example, relatively soft and cleaved black shale (Fermeuse Formation) gives rise to a fine till with acicular clasts; comparatively hard and jointed siltstone (Mistaken Point Formation) gives rise to cobbles and boulders, some of which may be large tabular plates. Siliceous clasts (Drook Formation) are locally abundant and have a white altered exterior due to intense leaching.

## Hummocky Till

Extensive areas of hummocky till occur throughout the map area, particularly between Cochrane Pond–Windsor Lake–Bauline (Figure 4). As seen in fresh excavations, this poorly consolidated till is yellowish brown, massive, poorly sorted and clast-rich. The coarser fraction forms 75 to 85 percent of the deposit and is mostly cobble size and has pebbles and boulders scattered throughout. Silty sand comprises the remaining 15 to 25 percent with the coarse sand component predominant. Analysis of the matrix by sieving shows silt-clay content to be 5 percent or less, suggesting much of the finer fraction was probably winnowed from the coarser detritus.

The largest and best exposures of hummocky till occur in a 10 km$^2$ area to the west and southeast of Windsor Lake. This area is characterized by irregular hillocks and unoriented rounded ridges of till with gentle (2 to 5 percent) to steep (10 to 20 percent) slopes of variable relief (generally between 5 and 20 m). Clast-dominated sheets of cobbles and boulders are exposed in hilly terrain with the intervening depressions containing bog or small ponds. The clasts are subangular and with minor exceptions, show little evidence of glacial abrasion such as polish and striae. Although most clasts are comparable in composition with the local bedrock, a small percentage reflect mixed sources suggesting a greater degree of glacial transport. This terrain was mapped and interpreted by Henderson (1972) as ablation moraine, in which lobes of ice stagnated during a late stage of deglaciation.

A less, well-developed hummocky-till veneer, occurs along the headwaters of South Brook and Waterford River, and between Mount Pearl and Bay Bulls Big Pond (Vanderveer, 1975; Batterson, 1984). These deposits are massive, poorly sorted and clast dominated, and were interpreted by Batterson (1984) as supraglacial melt-out tills.

As a result of land-clearing (for commercial and residential development), only vestiges of hummocky-till veneer can be seen in St. John's. In three, deep commercial excavations in drift, located within 400 m of the Elizabeth Avenue and Torbay Road intersection, the upper part of the working face consisted of thin (1 to 2.5 m), highly porous, cobble-dominated till (interpreted as supraglacial melt-out till) resting in sharp, but irregular contact, on thick (4 to 4.5 m), very compact, poorly sorted, matrix-dominated till (interpreted as lodgement till) with bedrock below.

## Lineated Till

The term 'lineated till' is used here to describe elongate ridges or mounds of surficial sediment that are generally, 5 to 10 m above the surrounding terrain and exhibit a pronounced parallel or sub-parallel orientation. In contrast with hummocky till, which originates from the disintegration of debris laden stagnant ice, lineated tills form below the flowing ice and are parallel to the flow (Boulton, 1970, 1972, 1976).

The largest examples of lineated till occur over a 25 km$^2$ low-lying area to the south and west of Tor Bay (Figure 4). To the north of Virginia Lake, glacial lineations (fluting) are defined by sub-parallel to sinuous northeast trending ridges and undulations, which were constructed in the till. Numerous brooks developed parallel to these features and now flow toward Logy Bay. There is also a prominent northeast alignment of lakes and ponds parallel to the direction in which the ice flowed. However, where streams cut through drift into bedrock, the streams abruptly change course and flow northward parallel to the orientation of rock structures (e.g., Outer Cove Brook).

In flat-lying areas near Bay Bulls Big Pond, the Goulds, Paradise, Donovans, Windsor Heights, and the Bauline Line–Bauline Road, there are long, ellipsoidal shaped mounds of glacially rounded till, which have a 'drumlinoid' characterization (Vanderveer, 1975). These linear features of variable relief (generally 5 to 10 m) were produced as the ice flowed across the till. However, it is possible that buried linear rock ridges may have influenced the development of some of these linear features.

Throughout the map area, and associated with the lineations are crag-and-tail features representing glacial deposition in the lee of bedrock knobs (Figure 4). Particularly good examples were observed between Mundy Pond and northeast Kenmount Hill during the construction of Columbus Drive. Till ramp-and-crag features (i.e., reversed crag-and-tail) were observed on small gabbro stocks near Paradise (Plate 7). In the Petty Harbour area, northerly trending boulder deposits along steeply dipping beds (e.g., in Saddle Hill and Petty Harbour) were pushed into place by eastward flowing ice; clasts were derived subglacially from several distinctive formations (e.g., Quidi Vidi and Gibbett Hill formations) within one kilometre of the depositional site (Plate 8).

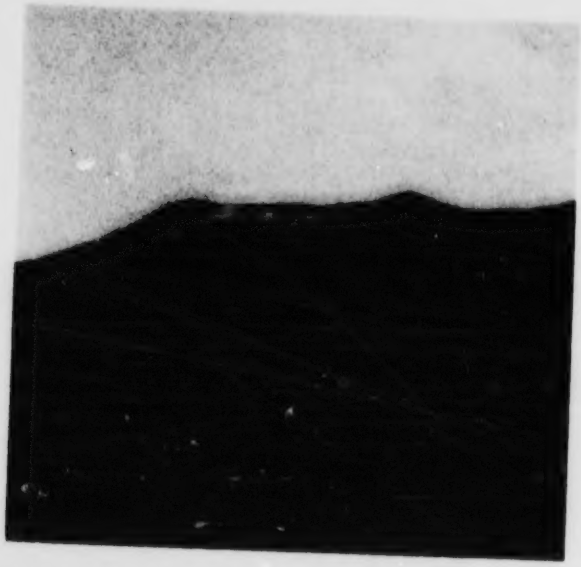


**Plate 7.** *Glacial striations and remnants of till ramp-and-crag (i.e., reversed crag-and-till) features on small gabbro stock near Paradise.*

## Boulder Fields and Erratic Boulders

Extensive boulder fields are rare in the map area. However, localized boulder fields are common, particularly in the Torbay–Bauline, Paddy's Pond–Cochrane Pond, and the Maddox Cove–Freshwater Bay areas. Dense concentrations (Plate 9) to more open clusters of cobbles and boulders exhibit a variety of compositions and surface textures. Most show some degree of rounding and attrition suggesting, at various times, transport by ice or by rapid meltwater streams.

Large (1 to 3 m) glacially transported boulders occur mainly as isolated erratics or in small clusters. They rest on till deposits or on bedrock. The boulder provenance is local with glacial transport generally 2 km or less and maximum

**Plate 8.** *Clast-dominated till (melt-out till) capping matrix-rich gravel (lodgement till), Petty Harbour Road (Goulds).*

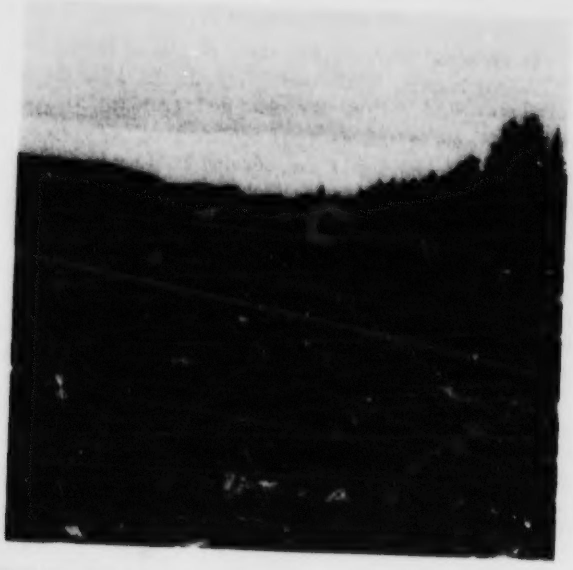


**Plate 9.** *Boulder field, Maddox Cove Road. Freshwater Bay in background.*

transport probably not exceeding 6 km (e.g., Conception Group erratics in the Signal Hill area). No granite (Holyrood Intrusive Suite) or Cambro-Ordovician erratics were found within the map area; as shown in Figure 4, the northern limit of granite erratic boulders is about 5 km south of Paddys Pond in the southwestern limits of the study area.

### Terraced Till

Terraced till consists of a series of step-like terraces with scarp faces and sub-horizontal surfaces cut in till. It constitutes a very minor part of the map area and is best exposed along the Waterford River valley (Batterson, 1984); the terraces are between 100 and 125 m a.s.l. Similar terraces are present along the southeast side of Kenmount Hill to the west of Branscombes Pond at a slightly higher elevation (about 125 to 150 m). A more dubious terrace (elev. 160 to 165 m) is present to the north of Brazil Pond. These terraces probably developed by meltwater being concentrated between the ice and the hills during deglaciation (Batterson, 1984, p. 21).

## ICE MOVEMENT AND DISPERSAL CENTRES

In an aerial photographic study of glacial fluting and drumlinoid features, Vanderveer (1975) postulated that during the late Wisconsinan glacial retreat, an ice divide developed along the height of land between Cochrane Pond–Donovans–Windsor Lake–Portugal Cove, causing local ice to move to the west and east. Field research by the writer supports Vanderveer's placement of this divide between Cochrane Pond and Windsor Lake (Figure 4). Orientation of glacial striae, roches moutonnées and lineations as well as erratic boulder provenance in the Broad Cove River–Portugal Cove area indicate paleoflow to the northwest (Figure 4). Roches moutonnées and glacial striae observed east of Octagon Pond, suggest ice movement toward the west-northwest (azimuth 290°), indicating a divide between Octagon and Bremigens Pond (King, 1984). Lineations and striae in an area 2 to 5 km south of Cochrane Pond, indicate a southeast flow of ice towards Bay Bulls.

The orientation of crag-and-tail ridges, striae and lineations east of Bremigens Pond, coupled with clast provenance analysis, suggest that a thin, topographically controlled, ice cover flowed in a curvillinear path across the Mount Pearl–Kenmount Hill area from west to northeast and then east via St. John's Harbour (Figure 4). Striae, chatter marks, polished surfaces, roches moutonnées and erratics, are common ice-related features of Signal Hill National Historic Park (see Plate 28, page 51) and demonstrate eastward movement of the ice. The Narrows, as well as Quidi Vidi Harbour (see Plate 30, page 51), Cuckold Cove, Robin Hood Bay, Logy Bay and Petty Harbour, have all been glacially eroded along highly fractured and jointed segments of otherwise resistant strata of the Signal Hill Group. Striae present on shales near the Logy Bay Road–Robin Hood Bay Road intersection indicate ice movement to the east (azimuth 090°); superimposed, lineated till, which formed sometime after the striae, indicate an east-northeast trend.

Striae and other ice-flow indicators present in the northern part of the map area (Figure 4) show a pronounced paleoflow toward the northeast (Plate 10). However, till clasts present in hummocky terrain along the Bauline Line are virtually in situ with respect to provenance. At Middle Three Island Pond, large (up to 2 m) boulders of amygdaloidal basalt (Harbour Main Group) occur 1.5 km east of the nearest exposure of the Princes Lookout Formation. It is probable that the sparse hummocky till represents a melt-out environment, which developed during deglaciation with some high-ground ice retreating toward Conception Bay. Therefore, it may be more appropriate to extend Vanderveer's (1975) ice divide from Windsor Lake northward along the high ground west of the Bauline Line, rather than to Portugal Cove (Figure 4). Roches moutonnées, striae and erratics in the Bauline area indicate ice flow to the west.

**Plate 10.** *Glacial striae, Flat Rock. (Photograph courtesy of Ben Hansen)*

## DEGLACIATION

During the late Wisconsinan, glacial ice on the Avalon Peninsula was sustained by heavy snowfall between 13,000 and 11,000 years BP (Macpherson, personal communication, 1988). Isotopic dating and paleobotanical studies of peat bogs and lake sediments by Macpherson (1981, 1982, 1985) indicate that after 11,000 years BP, the climate of the Avalon Peninsula changed significantly, causing a gradual retreat of the ice sheet and the release of vast quantities of meltwater.

Macpherson (1981, 1982, 1985), using radiocarbon-dated pollen profiles of lake sediments, suggested downwasting of the final ice-mass on the eastern Avalon Peninsula after about 10,500 years BP, when the central upland Hawke Hills emerged (e.g., 10,100 ± 250 years, GSC-3136 from Golden Eye Pond, Butterpot Provincial Park). She also suggested that ice disappeared on the lower coastal ground near St. John's probably as late as 9700 years BP (e.g., 9440 ± 360 years, GSC-3182 from Oxen Pond; 9270 ± 150 years, GSC-2601 from Sugar Loaf Pond; 8570 ± 90 years, GSC-3618 from Kenny's Pond). After 9300 years BP, a rich shrub tundra at lower elevations was invaded by spruce, balsam fir and birch until at ca. 8400 years BP the vegetation was an open woodland (Macpherson, 1982). Peat from a bog west of the Goulds gave a radiocarbon age of 7400 ± 150 years BP and a palynological study of pollen, from below the peat, indicated that at about 7500 years BP, spruce, fir, birch, pine and alder were established in the area (Henderson, 1972). The presence of abundant tree stumps and roots along the base of excavated bogs in the St. John's area, supports this contention and indicate that the bogs themselves were sites of conifer growth.

## POSTGLACIAL DEPOSITS

### Fluvial and Lacustrine Deposits

Glaciofluvial and postglacial fluvial deposits are small, although glacial meltwaters were probably abundant during deglaciation. Thin deposits of alluvium occur to the southwest of Bremigens Pond and in several narrow tracts along the Waterford River, east of Donovans (Batterson, 1984); very narrow and restricted flood-plain deposits that consist of fluvial silts, sands and gravels are also present along some of the other rivers and brooks in the map area.

Bottom sediments from lakes in the St. John's area have been cored by Macpherson (e.g., 1981, 1982, 1985). The longest core from Sugar Loaf Pond shows a postglacial transition from mineral sediment (laminated silty clay) to organic sediment; radiocarbon dated samples from the basal part of the core indicate variable sedimentation rates, generally in the order of 14 cm per 250 years (Macpherson, 1982, p. 179).

### Organic Deposits and Soils

Numerous isolated deposits of organic and peaty soils comprise about 5 percent of the map area. The shape, size, and thickness of the deposits were influenced by the geometry and water depth of the ponds and drainage systems in which they accumulated, after deglaciation. Bogs more than 5 m deep were encountered in excavations for pipelines, to the west of the Goulds. A large tract of organic terrain and peaty soils in the vicinity of Cochrane Pond has been reclaimed for agricultural use.

Organic and mineral soils of the Avalon Peninsula have been classified by both Page (1971) and by Heringa (1981). Based on their studies, most of the mineral soils in the map area belong to two major soil orders—podzols and gleysols. Podzols are most abundant but are generally thin (< 0.5 m) and acidic (e.g., pH 4.5 to 5). They developed under a forest cover dominated by fir, spruce and birch. Soils of the gleysolic order developed under reducing conditions in drainage systems supporting hydrophytic vegetation (e.g., low growing juniper and heath).

### Mass-Wasting Deposits

Material classified as colluvium (i.e., formed by mass movement of deposits down valley slopes), was recognized by Henderson (1972, p. 100) at several places along the lower Waterford River valley. In the upper and middle parts of the Broad Cove River valley, deposits of glacial drift show evidence of postglacial solifluction (Brückner, 1979, p. 14).

Minor talus deposits are present on some of the coastal hills. Rockslides, rockfalls, debris flows and avalanches are infrequent, but at times have been catastrophic (e.g., the Battery avalanche of 1959). Low-lying areas situated below steep slopes are potentially hazardous and include the lower Battery and South Side Road (east of St. John's Harbour), Portugal Cove, St. Phillips, St. Thomas, and Petty Harbour. Marine erosion has removed much of the surficial and mass-wasting deposits from coastal cliffs.

### Marine Deposits

Small beaches at Outer, Middle and Beachy coves, consist of pebbles and cobbles eroded from adjacent drift-filled valleys. The finer fraction comprising the drift is winnowed away by storm waves and deposited offshore.

Barachois or bay-mouth bars and associated lagoons are present at Freshwater Bay, Flat Rock and Broad Cove (St. Phillips). The beach in Freshwater Bay is made up of large cobbles and small boulders that form a low bar (about 3 m a.s.l.), separating the bay from a lagoon (Freshwater Bay Pond). Strong storm waves and currents from the northeast produced the bar; twisted and torn scraps of metal from shipwrecks attest to the strength of the currents. A less, well-developed barrier bar with a tiny lagoon can be seen at Flat Rock Cove. At Broad Cove, a man-made channel has been cut through the bar and the lagoon has been dredged for small-boat use. Longshore currents are responsible for the numerous barrier bars and spits in southeastern Conception Bay (Brückner, 1979, p. 21).

Remnants of raised shorelines above the present sea level indicate submergence of low-lying areas during early postglacial time. At the south end of St. Thomas Cove, remnants of a sand and gravel beach-deposit overlie a raised bedrock platform of about 6 m a.s.l. (Brückner, 1979, p. 16). The rocky platform beneath Fort Amherst, about 2 to 3 m a.s.l., may also indicate early postglacial submergence and marine erosion (Brückner, 1979, p. 6).

### Land Fill

Man-made deposits of fill are widespread throughout the map area, particularly in sites formerly occupied by peat bogs.

Land-fill deposits are used for commercial, engineering and residential purposes and range in thickness from 1 to 10 m. Sources of materials include rock from quarries and till.

With respect to till provenance studies and geological mapping, care must be taken to distinguish between man-made and natural deposits. For example, volcanic rocks from the former quarry at Portugal Cove were used in retaining walls around Windsor Lake, St. John's shale was used as back-fill north of Adams Pond (Paradise), and crushed stone (Holyrood granite) is used in construction projects throughout the Avalon Peninsula.

## SURFACE WATER AND GROUNDWATER

### Drainage

The main rivers draining the St. John's area are shown on the accompanying maps and Figure 1. These include Waterford, Petty Harbour, Broad Cove, Horse Cove, Northeast Pond, Virginia, and Rennie's rivers. Additional drainage is provided by numerous small streams such as South, Beachy Cove, Piccos, Island Pond, North Pond, Kennedys, Soldiers, Outer Cove, Leamys, and Spear Bay brooks.

The Waterford River basin is centred around the rapidly expanding city of Mount Pearl and drains an area of about 60 km$^2$. The Waterford River has a generally eastward flow and extends from Bremigens Pond to St. John's Harbour, a distance of 14 km. The main tributary of South Brook is bordered by farmland and has its source about 2 km south of Bremigens Pond. This basin has been the focus of considerable study (e.g., Rhodenizer, 1972; Heringa, 1981; Batterson, 1984; King, 1984; Gale *et al.*, 1984). The mean annual basin-yields, for the Waterford River at Kilbride, average 0.041m$^3$/s/km$^2$ (for the period 1974-1982) or, equivalent to about 1300 mm of precipitation (Gale *et al.*, 1984, p. 104).

Broad Cove River with its tributaries, drains an area of about 35 km$^2$ and is the largest stream in the map area flowing into Conception Bay. The headwater area lacks significant relief with gentle (2 to 5 percent) slopes.

### Water Supply

Lakes and small ponds cover about 7 percent of the map area; most have an east-northeast to northeast trend. Surface waters are presently adequate in supplying the fresh water needs of most of the City of St. John's, the City of Mount Pearl and the larger surrounding towns. Windsor Lake, Bay Bulls Big Pond and Petty Harbour Long Pond (elev. 164 m) are important reservoirs supplying domestic water to St. John's, Mount Pearl and other local towns.

Windsor Lake (elev. 150 m) occupies a shallow structural basin and ultimately drains into Broad Cove River via a number of ponds. Extensive, irregularly shaped bogs and marshes between Windsor Lake and Paradise act as sponges to absorb the rainfall. Small dams raise the water levels of Windsor Lake and some of the larger ponds in the vicinity of Thorburn Road to increase the water reserves.

The surface waters of the Avalon Peninsula have low pH values (generally between 4 and 6.5) and, since average alkalinity and hardness values are less than 10 mg/L (Gale *et al.*, 1984), these reservoirs are susceptible to the effects of acid rain caused by atmospheric pollution. Surface water quantity and quality data for the Avalon Peninsula, based mainly on readings at stream-gauging stations, are published by the Water Resources Branch of Environment Canada and Newfoundland Department of Environment and Lands.

Within the rural parts of St. John's, Mount Pearl and in the eleven surrounding towns, numerous households are dependent upon shallow dug wells in till, or upon deeper drilled wells located mainly in bedrock. Water supplied to these wells is from precipitation (e.g. approximately 1500 mm a year at St. John's Airport), but only about 20 to 25 percent of this recharges the groundwater table, the rest is lost to surface runoff, and evapotranspiration (Gale *et al.*, 1984).

### Water Quantity in Surficial Deposits

The surficial deposits within the Avalon Peninsula have been divided into two surficial hydrostratigraphic units, the first consisting primarily of undifferentiated tills and the second consisting of outwash plain and kame deposits (Gale *et al.*, 1984). Hydrostratigraphic units, as the term is used here, are surficial formations or units with similar hydrologic characteristics and provide a basis for a first approximation of the groundwater potential of a given area.

In the map area, compact-veneer till is a low-permeability aquifer and perhaps most representative of the first unit, which produces average yields of less than 9L/min, (based on assumed hydraulic conductivities of $10^{-7}$ to $10^{-10}$ m/sec for a 2 m deep well, 1 m in diameter with full drawdown). Wells in thin-veneer till are prone to very low yields under hot summer conditions. Although hummocky till was included within the first unit, all the hummocky tills observed in the map area, by the writer, showed high permeability (in excavations within hummocky till, pumps were required to prevent flooding). Their potential should be assessed because mean-yield values should be closer to those of the second hydrostratigraphic unit (mean yield 40.6 L/min). Major drainage ditches or trenches dug in tills with a perched water table (e.g., Airport Heights) are known to have had a very adverse effect on shallow wells in close proximity.

The negative effects of urban development on the movement of water through the Waterford River basin as expressed by Batterson (1984, p. 22) are now known to be valid and have regional implications. Batterson (1984) postulated that removal of vegetation and trenching or excavating the critical supraglacial till on the east and south side of Kenmount Hill, will reduce the overall storage capacity of the ground water environment and will accelerate the

**Table 2:** Hydrogeological characteristics of bedrock units on the Avalon Peninsula including wells within these units in the St. John's area (adapted from Gale *et al.*, 1984, p. 73-79)

| Rock Group | Rock Type | No. of Wells** | Well Depth (m) | | Well Yield (L/min) | |
|---|---|---|---|---|---|---|
| | | | Mean | Range | Mean | Range |
| Wabana/Bell Island* | Sandstone, siltstone shale, oolitic ironstone | 14 | 77 | 21-201 | 73.5 | 6.8-273.0 |
| Holyrood* Intrusive Suite | Granitoid rocks | 22 | 52 | 7-155 | 27.6 | 2.3-136.5 |
| Signal Hill | Breccia, conglomerate sandstone, | 18 | 50 | 12-111 | 430 | 1.1-273.0 |
| St. John's | Shale, sandstone | 92 | 54 | 7-155 | 26.2 | 1.1-227.5 |
| Conception | Siliceous sandstone and siltstone, mixtite, volcaniclastics | 211 | 52 | 9-153 | 20.4 | 0.6-136.5 |
| Harbour Main | Volcanic and sedimentary rocks, mafic and silicic intrusions | 74 | 41 | 7-122 | 24.5 | 1.1-136.5 |

* adjacent to St. John's map area and shown for comparison. ** numbers refer to wells throughout Avalon Peninsula including St. John's area

surface flow into the drainage system. During periods of intense rainfall in 1985 and 1986, man-made channels were unable to cope with the discharge and flooding took place in a new commercial and residential development east of Branscombes Pond. The rapid increase of water into the Waterford River, as a result of urban drainage, has increased erosion further downstream and has also increased the flooding potential. With further commercial development on the north side of Kenmount Hill, especially the large catchment area west of the Avalon Mall between Thorburn and Kenmount Road, the risk of dry-wells and flooding can be anticipated.

### Water Quality of Shallow Wells

A review of the available data (e.g., Newfoundland Department of Environment and Lands, Water Quality Reports; Gale *et al.*, 1984) and inquiries made in the field (approximately 200), show that water-quality problems in dug wells, relate mostly to high manganese concentrations associated with high iron values. The manganese and iron are often leached from the soil, overburden or rock. Elevated chloride values (NaCl; $CaCl_2$) in some shallow wells within 10 to 15 m of main roads (e.g., Airport Heights; Thorburn Road) are due mainly to road-salt contamination. High nitrate levels in some dug wells (e.g., in Torbay, Thorburn Road, Paradise and in the Goulds) suggest contamination from a source such as animal manure, septic waste or chemical fertilizer. In some wells, surface drainage systems, and ponds (e.g., Western Island Pond), pollution from seeping or overflowing liquid-manure holding-dams is suspected. The number of wells in the St. John's area, which are polluted as a result of indiscriminate dumping of solid and liquid waste is uncertain, but three to four cases are reported every year (J. Robinson, personal communications, 1987, Newfoundland Department of Environment and Lands).

## GROUNDWATER POTENTIAL OF BEDROCK UNITS

The groundwater potential of bedrock units in the Avalon Peninsula was recently assessed by Gale *et al.* (1984), based largely on water-well data, supplied by the Water Resources Division, Newfoundland Department of Environment and Lands. A generalized summary of the hydrogeological characteristics of bedrock units in the map area is shown in Table 2.

From a hydrogeological perspective, fractures include joints, fracture zones and shear zones. In rock masses such as those found in the St. John's area, the hydraulic characteristics are predominantly a result of the interconnection of the different joint sets; bedding planes, if open (e.g., locally on Signal Hill–Southside Hills) form conduits similar to joints. However, most clastic sedimentary bedrock units of the map area and the Avalon Peninsula in general, are well cemented and have very low matrix (primary) porosity and permeability with values approaching those for most metamorphic and granitic rocks (Gale *et al.*, 1984); hence, at least in the near surface, fractures are the primary conduits for groundwater movement.

Open-fracture zones (i.e., closely spaced, highly interconnected discrete fractures) are characteristic of the siliceous volcaniclastic sedimentary rocks (e.g., Drook Formation), which comprise much of the central part of the map area. Iron (derived from weathered pyrite, hematite and magnetite) and manganese (pyrolusite) are common stains along fracture surfaces and indicate that fracture zones and, to a lesser extent, bedding surfaces are the primary conduits for groundwater movement in these otherwise well-cemented, low matrix porosity rocks. However, some coarse-grained volcaniclastic rock units (e.g. facies C-4c of the Torbay Member) appear to be an exception and may have good potential as an aquifer.

Steeply dipping, irregular fractures are characteristic of the more argillaceous bedrock units (especially the Hibbs Cove Member of the Mistaken Point Formation). These argillaceous units are very susceptible to frost action (Plate 11); they underlie Windsor Lake and provide a very important conduit for groundwater movement into the basin. Slaty cleavage is characteristically well developed in the shales in the Outer Cove–St. John's–Mount Pearl areas (e.g., Trepassey, Fermeuse, and Renews Head formations). The north-northwest trending slaty cleavage in the Newtown–Mount Pearl area provides a conduit for groundwater movement and the migration of iron and manganese.

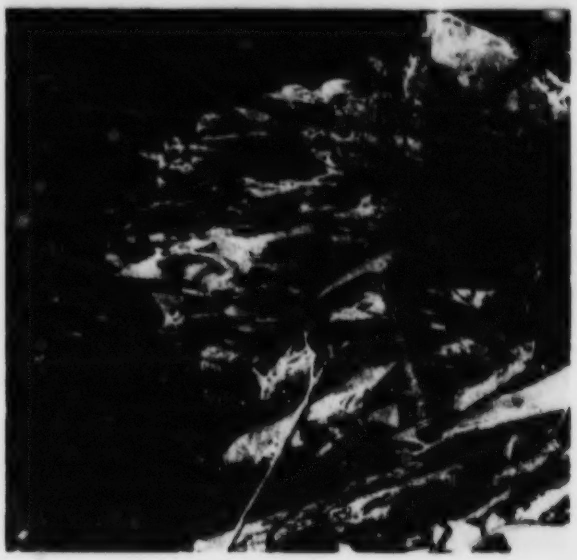


**Plate 11.** *Frost-shattered till composed of boulders of Hibbs Cove Member (Mistaken Point Formation), Windsor Lake.*

# GEOLOGY OF THE ST. JOHN'S AREA

## INTRODUCTION

### Regional Geological Setting

The Appalachian Orogen in Newfoundland is divided into four main tectono-stratigraphic zones (Figure 5, index map), each displaying a distinctive pre-Silurian evolutionary history (Williams, 1971, 1976, 1978; Williams and Hatcher, 1983). The Avalon Zone lies to the east of the Dover–Hermitage Bay Fault (Blackwood and Kennedy, 1975; Blackwood and O'Driscoll, 1976). Genetic links across this fault are not evident until the Devonian, when sediments deposited in the Avalon Zone contain detritus from the adjacent Gander Zone. Final juxtaposition of the Gander and Avalon zones was completed prior to the intrusion of the 360 ± 5 Ma, posttectonic Ackley Granite (Dallmeyer *et al.*, 1981, 1983).

The Avalon Zone in Newfoundland is a terrane consisting of mainly thick sequences of Precambrian volcanic and sedimentary rocks, locally overlain by Paleozoic sedimentary rocks having body and trace fossils, characteristic of the Atlantic realm. Bimodal volcanic rocks, which formed mainly in a subaerial environment, are diagnostic of the Avalon Zone. In Newfoundland, these rocks are exposed in separate, mainly northeast trending belts. Comagmatic with these volcanic rocks are foliated, hornblende and biotite calc-alkaline granite and granodiorite plutons. Rocks of similar age and facies occur in Nova Scotia (Keppie, 1982), New Brunswick (Ruitenberg *et al.*, 1973) and throughout the Appalachian Orogen in the eastern United States (Rast, 1980; Skehan and Murray, 1980; Hatcher *et al.*, 1980). The Avalon Zone continues in the offshore Grand Banks of Newfoundland for about 250 km to the present continental margin (Lilly, 1966; Haworth and Lefort, 1979; King *et al.*, 1986). Similar rocks occur in the southern part of the British Caledonides, the Hercynides of France and Iberia and in the northern and eastern margin of the west African shield (e.g., Rast *et al.*, 1976; Rast, 1980; O'Brien *et al.*, 1983; King and O'Brien, in press).

The Avalon Peninsula is geologically part of the Avalon Zone. As shown in Figure 3 and by King (1988), it consists of a thick, relatively unmetamorphosed Precambrian (Proterozoic III: ca. 750 to 570 Ma) succession, which contains in ascending order, volcanic (Harbour Main Group), turbiditic (Conception Group), basinal–deltaic (St. John's Group), and molasse-like rocks (Signal Hill Group). These groups define major elongate structural domes and basins. The rocks were first deformed in the Precambrian Avalonian Orogeny and subsequently regionally deformed and metamorphosed during the mid-Paleozoic Acadian Orogeny. The volcanic rocks were intruded during the closing stages of the Avalonian Orogeny by granitoid rocks of the Holyrood Intrusive Suite which are $620.5^{+2.1}_{-1.8}$ Ma old (Krogh *et al.*, 1983, 1988). Both volcanic and granitoid rocks are unconformably overlain in eastern Conception Bay by fossiliferous Cambrian and Ordovician marine-shelf sedimentary rocks.

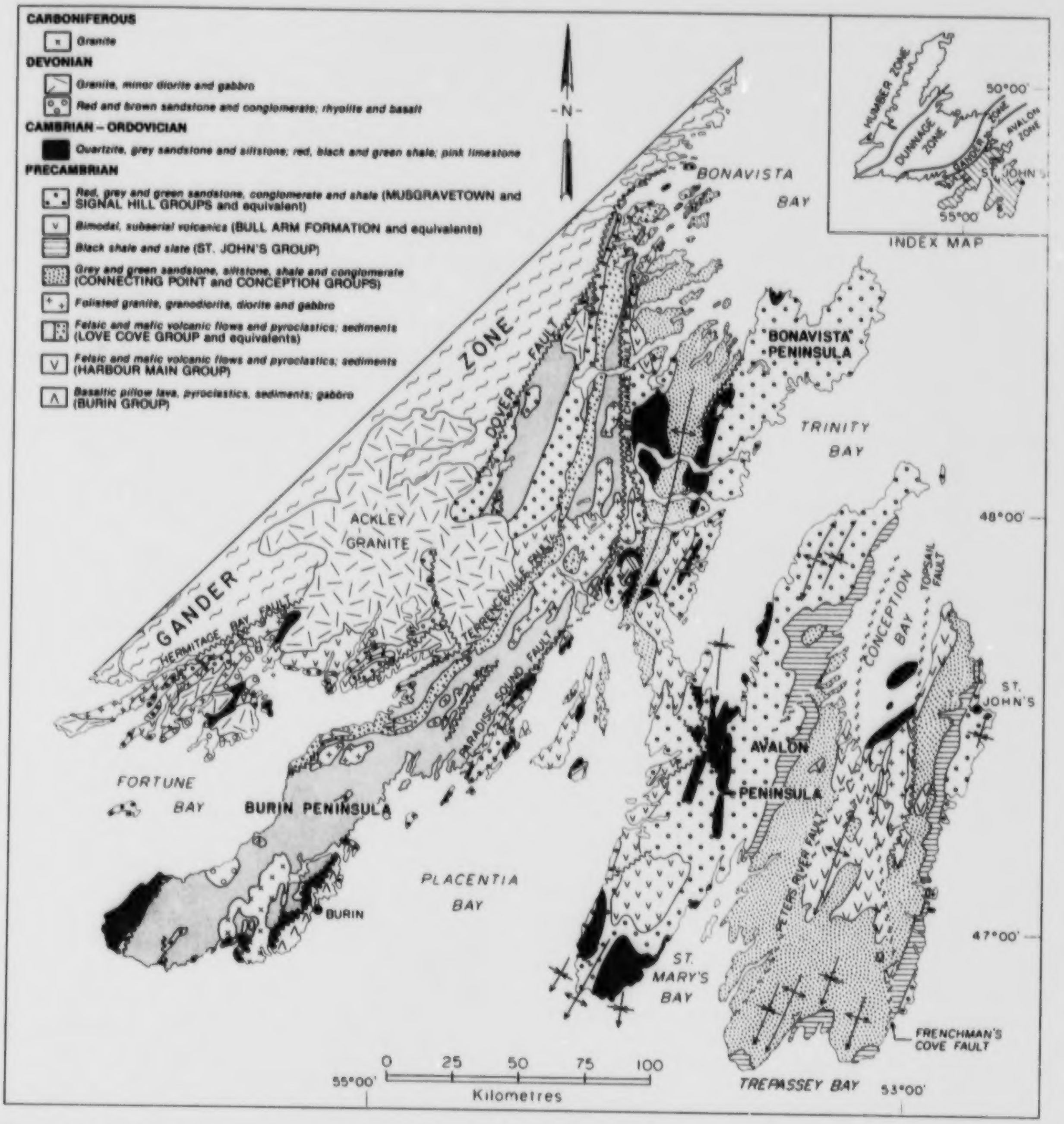

CARBONIFEROUS
Granite
DEVONIAN
Granite, minor diorite and gabbro
Red and brown sandstone and conglomerate; rhyolite and basalt
CAMBRIAN – ORDOVICIAN
Quartzite, grey sandstone and siltstone; red, black and green shale; pink limestone
PRECAMBRIAN
Red, grey and green sandstone, conglomerate and shale (MUSGRAVETOWN and SIGNAL HILL GROUPS and equivalent)
Bimodal, subaerial volcanics (BULL ARM FORMATION and equivalents)
Black shale and slate (ST. JOHN'S GROUP)
Grey and green sandstone, siltstone, shale and conglomerate (CONNECTING POINT and CONCEPTION GROUPS)
Foliated granite, granodiorite, diorite and gabbro
Felsic and mafic volcanic flows and pyroclastics; sediments (LOVE COVE GROUP and equivalents)
Felsic and mafic volcanic flows and pyroclastics; sediments (HARBOUR MAIN GROUP)
Basaltic pillow lava, pyroclastics, sediments; gabbro (BURIN GROUP)
N
HUMBER ZONE
DUNNAGE ZONE
GANDER ZONE
AVALON ZONE
ST. JOHN'S
50°00'
55°00'
INDEX MAP
BONAVISTA BAY
GANDER ZONE
DOVER FAULT
"BONAVISTA" PENINSULA
TRINITY BAY
ACKLEY GRANITE
HERMITAGE BAY FAULT
TERRENCEVILLE FAULT
PARADISE SOUND FAULT
48°00'
CONCEPTION BAY
TOPSAIL FAULT
ST. JOHN'S
AVALON PENINSULA
FORTUNE BAY
BURIN PENINSULA
BURIN
PLACENTIA BAY
PETERS RIVER FAULT
47°00'
ST. MARY'S BAY
FRENCHMAN'S COVE FAULT
0 25 50 75 100
Kilometres
55°00'
TREPASSEY BAY
53°00'

**Figure 5.** *Simplified geological map of the Avalon Zone in Newfoundland (after King and O'Brien, in press). The index map illustrates the major tectonostratigraphic zones of the Newfoundland Appalachians.*

## Local Geological Setting

The oldest rocks on the Avalon Peninsula comprise a bimodal volcanic assemblage, the Harbour Main Group (Figures 3 and 6). Volcanic and volcaniclastic rocks of the Harbour Main Group, exposed in the map area along the eastern shore of Conception Bay, are presumed to be conformably overlain by the Conception Group (Figure 7), the most widespread marine clastic sequence on the Avalon Peninsula (Figure 3). A thick, marine sequence of dominantly green, siliceous sedimentary rocks of the Conception Group is present between the high western coastal range and the western limits of the city of St. John's. The Conception Group is conformably overlain by a shallowing-upward marine

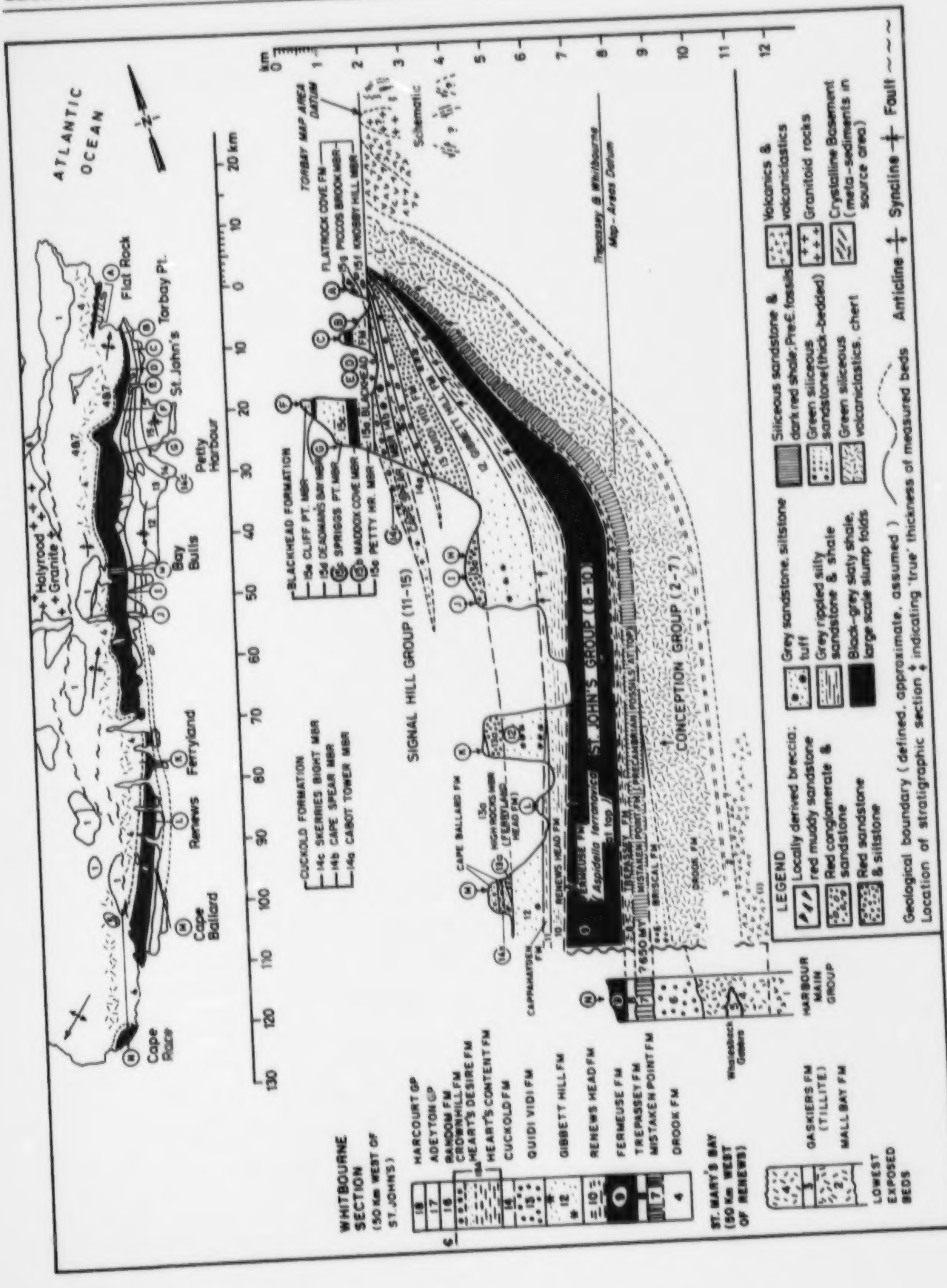

ATLANTIC OCEAN
N
Flat Rock
Torbay Pt.
St. John's
Petty Harbour
Bay Bulls
Holyrood Granite
Ferryland
Renews
Cape Ballard
Cape Race
0 10 20 30 40 50 60 70 80 90 100 110 120 130
20 km
km
TORBAY MAP AREA DATUM
Schematic
FLATROCK COVE FM
15i PICCOS BROOK MBR
15i KNOBBY HILL MBR
BLACKHEAD FORMATION
15e CLIFF PT. MBR
15d DEADMAN'S BAY MBR
15c SPRIGGS PT. MBR
15b MADDOX COVE MBR
15a PETTY HR. MBR
CUCKOLD FORMATION
14c SKERRIES BIGHT MBR
14b CAPE SPEAR MBR
14a CABOT TOWER MBR
SIGNAL HILL GROUP (11-15)
ST. JOHN'S GROUP (8-10)
CONCEPTION GROUP (2-7)
CAPE BALLARD FM
HIGH ROCKS MBR
FERRYLAND HEAD FM
RENEWS HEAD FM
FERMEUSE FM
Aspidella terranovica
TREPASSEY FM
MISTAKEN POINT FM
PRECAMBRIAN FOSSILS
BRISCAL FM
DROOK FM
?650 MY
CAPPAHAYDEN FM
Trepassey & Whitbourne Map-Areas Datum
WHITBOURNE SECTION (50 Km WEST OF ST. JOHN'S)
HARCOURT GP
ADEYTON GP
RANDOM FM
CROWNHILL FM
HEART'S DESIRE FM
HEART'S CONTENT FM
CUCKOLD FM
QUIDI VIDI FM
GIBBETT HILL FM
RENEWS HEAD FM
FERMEUSE FM
TREPASSEY FM
MISTAKEN POINT FM
DROOK FM
ST. MARY'S BAY (50 Km WEST OF RENEWS)
GASKIERS FM (TILLITE)
MALL BAY FM
LOWEST EXPOSED BEDS
Whiteshack Gabbro
HARBOUR MAIN GROUP
LEGEND
Locally derived breccia; red muddy sandstone
Red conglomerate & sandstone
Red sandstone & siltstone
Grey sandstone, siltstone
tuff
Grey rippled silty sandstone & shale
Black-grey slaty shale, large scale slump folds
Siliceous sandstone & dark red shale; Pre€ fossils
Green siliceous sandstone (thick-bedded)
Green siliceous volcaniclastics, chert
Volcanics & volcaniclastics
Granitoid rocks
Crystalline Basement (meta-sediments in source area)
Geological boundary ( defined, approximate, assumed )
Location of stratigraphic section indicating 'true' thickness of measured beds
Anticline
Syncline
Fault

**Figure 6.** *Stratigraphic profile of the Upper Precambrian units, eastern Avalon Peninsula (modified after King, 1982).*

sequence of dark-grey shale and sandstone of the St. John's Group, which occurs in the eastern part of the map area. A thick alluvial-plain sequence, the Signal Hill Group, conformably overlies the St. John's Group and forms the eastern range of hills in the map area. The group is presumed to be latest Precambrian to possibly Early Paleozoic.

Small stocks of diabase and gabbro are present in the Dogberry Hill area, about 1 km northwest of Ryalls Pond, but their age and relationships to the Harbour Main and Conception groups are uncertain.

### Formation Nomenclature and Proposed New Subdivisions

A summary of formal stratigraphic units used in the Atlantic region is presented in Williams *et al.* (1985).

Volcanic and volcaniclastic rocks of the Harbour Main Group (Rose, 1952), are here formally divided into three new formations, St. Phillips, Princes Lookout and Portugal Cove; the first includes the Beachy Cove Member. These proposed units represent the first formal regional divisions of this group. Their relative stratigraphic position is uncertain.

The Conception Group nomenclature is essentially that of Williams and King (1979). Their Drook and Mistaken Point formations have been traced northward throughout most of central and eastern Avalon Peninsula by King (1980, 1982, 1988) and are shown in Figure 3. Local and regional lithological correlations indicate a moderate degree of formational homogeneity (King, 1980). The Drook Formation in the map area is subdivided into five new members, which in ascending order are Broad Cove River, Bauline Line, Torbay and Mannings Hill; a fifth member, Octagon Pond, is a possible correlative of the Broad Cove River. The Mistaken Point Formation is subdivided into two new members, the lower Middle Cove Member and the upper Hibbs Cove Member.

St. John's Group divisions are those of Williams and King (1979). These include, in ascending stratigraphic order, the Trepassey, Fermeuse and Renews Head formations (Figure 6).

The Signal Hill Group nomenclature of Williams and King (1979) is retained in this report. Green sandstones of the Gibbett Hill Formation (King, 1972a) are gradational and conformable with the irregularly bedded Renews Head sandstones of the St. John's Group. There is erosional truncation of Gibbett Hill beds by red sandstones of the Quidi Vidi Formation (King, 1980). Red conglomerates and arkoses of the Cuckold Formation (King, 1972a) are gradational with underlying rocks of the Quidi Vidi Formation and overlying red sandstones of the Blackhead Formation (Hayes, 1931; Rose, 1952). The Cuckold Formation of the Signal Hill Group is here subdivided into three new members, which in ascending order are Cabot Tower, Cape Spear, and Skerries Bight. The Blackhead Formation is subdivided into five new members, which in ascending stratigraphic order are Petty Harbour, Maddox Cove, Spriggs Point, Deadman's Brook, and Cliff Point. The Flat Rock Cove Formation (King, 1982) is only present at Flat Rock Cove, where it appears to stratigraphically overlie the Skerries Bight Member of the Cuckold Formation; it consists of two members, Knobby Hill and Piccos Brook.

Prominent gabbro and diabase stocks, which are best exposed along the eastern fault-bounded margin of the Harbour Main Group are here formally referred to as the Dogberry Hill Gabbro. The volcanic rocks of the Harbour Main Group on the Avalon Peninsula are intruded by granitoid rocks of the Holyrood Plutonic Series (McCartney *et al.*, 1966), subsequently renamed Holyrood Intrusive Suite (O'Driscoll and King, 1985); it is uncertain, however, if the small exposures of foliated granitoid rocks in the map area are part of this suite. Major folds and faults are named and are discussed in the structural geology and metamorphism section. In the following account, unit numbers are placed in brackets after the stratigraphic names and facies to facilitate easy reference.

## HARBOUR MAIN GROUP (UNITS 1 to 3)

### Definition

The Harbour Main Group of central and eastern Avalon Peninsula, comprises a thick succession of volcanic and volcaniclastic strata (Figure 3). Buddington (1916) proposed the name 'Avondale Volcanics', which was subsequently changed to the 'Harbour Main Volcanics' (Howell, 1925), and later to the 'Harbour Main Group' (Rose, 1952).

The Harbour Main Group is exposed in three, lithologically distinct, fault blocks (Papezik 1969, 1970; Nixon and Papezik, 1979). The western block includes the type locality of Avondale–Harbour Main. The group is undivided and characterized by well preserved red, pink, and grey ignimbrites, locally intercalated with fluvial volcanogenic sedimentary rocks and overlain by terrestrial fissure-type flows of dark green to purplish, massive and amygdaloidal basalt (McCartney, 1967). These rocks have been metamorphosed under conditions of the prehnite–pumpellyite-facies. Krogh *et al.* (1983, 1988) report U–Pb zircon dates of $606^{+3.7}_{-2.9}$ Ma on ash-flow tuff and $622.6^{+2.3}_{-2.0}$ Ma on rhyolite from Colliers Peninsula and near the community of Harbour Main, respectively. On the basis of their chemistry and mineralogy, the mildly alkaline mafic flows of the Harbour Main Group at Colliers Bay are classified as hawaiites and mugearites and have intraplate chemical affinities (Papezik, 1970; Nixon and Papezik, 1979). The central block, to the west of the Topsail Fault, includes felsic and mafic flows, pyroclastics and minor volcaniclastics, intruded by high-level granite, quartz–monzonite and granodiorite of the Holyrood Intrusive Suite (Figure 3). Volcanic and volcaniclastic rocks of the eastern block are brought up along the Topsail Fault, which follows the eastern shore of Conception Bay. This volcanic belt defines the high coastal range in the western part of the St. John's map area, and is dominated by pillow lava and associated volcaniclastic sedimentary rocks (Figure 7). Rhyolite domes, dated at 585 Ma (U–Pb zircon date, Krogh *et al.*, 1983, 1988), intrude the volcanic and sedimentary assemblage in the Cape St. Francis area (Figure 3).

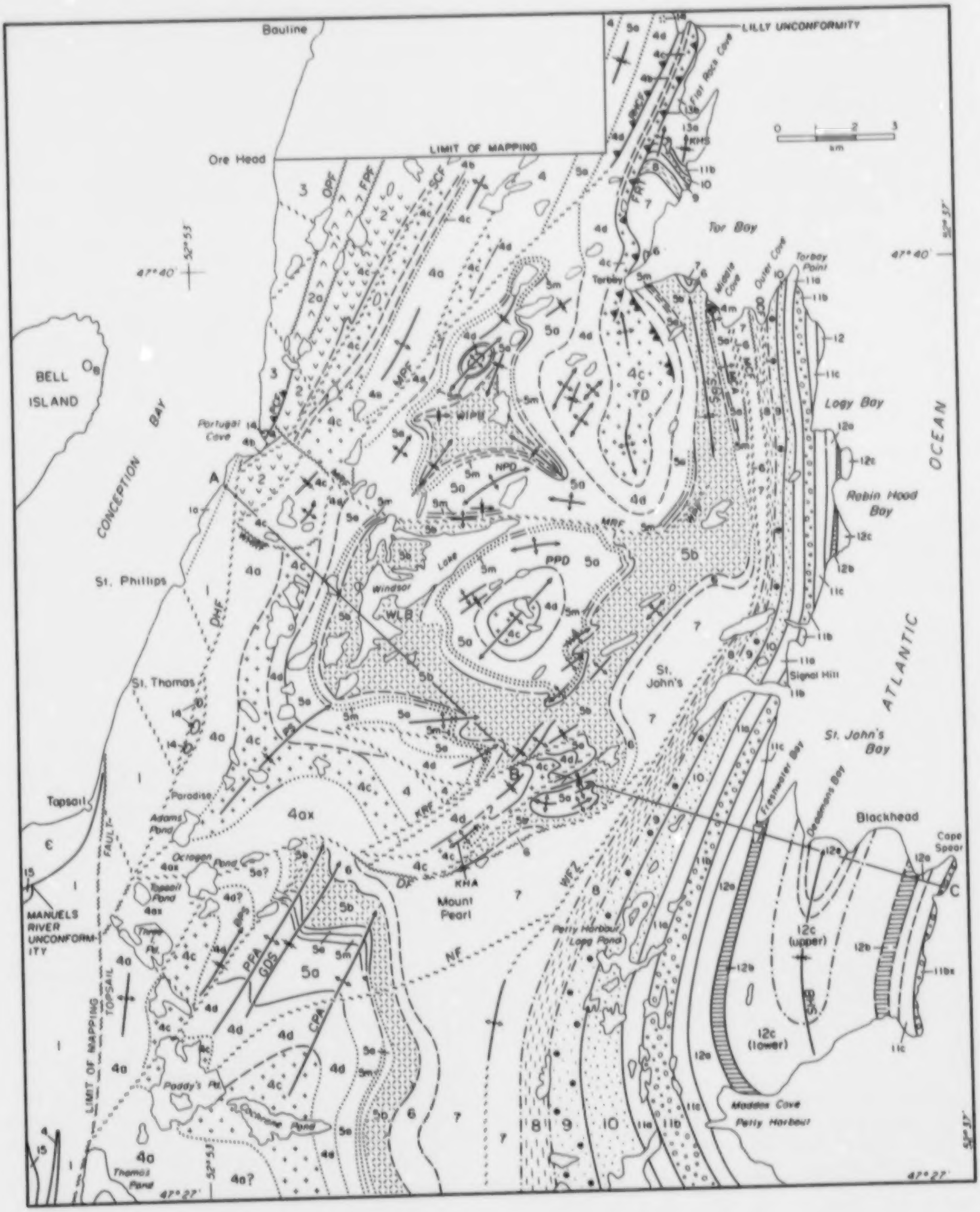

Bauline
LILLY UNCONFORMITY
Flat Rock Cove
LIMIT OF MAPPING
Ore Head
0 1 2 3
km
Tor Bay
Torbay
Middle Cove
Outer Cove
Torbay Point
47° 40'
52° 37'
52° 53'
BELL ISLAND
Portugal Cove
CONCEPTION BAY
Logy Bay
OCEAN
Robin Hood Bay
Windsor Lake
WLB
PPD
NPD
WIPH
TD
MRF
St. Phillips
DHF
St. Thomas
St. John's
Signal Hill
ATLANTIC
St. John's Bay
Topsail
Paradise
Adams Pond
4ax
KRF
Blackhead
Cape Spear
A
B
C
Octagon Pond
Topsail Pond
MANUELS RIVER UNCONFORMITY
TOPSAIL FAULT
Mount Pearl
KHA
NF
WFZ
Petty Harbour Long Pond
Freshwater Bay
Deadmans Bay
12c (upper)
12c (lower)
PPA
GDS
CPA
Paddy's Pd.
LIMIT OF MAPPING
Thomas Pond
Maddox Cove
Petty Harbour
47° 27'
47° 27'
52° 53'
52° 37'

Figure 7. *Geological map of the St. John's area. A-B-C transect illustrated in Figure 27.*

# LEGEND

**ORDOVICIAN**

**BELL ISLAND AND WABANA GROUPS**

Os *Sandstone, shale ironstone*

**CAMBRIAN**

**ADEYTON AND HARCOURT GROUPS**

C *Shale*

**PROTEROZOIC III (Late Precambrian; may include minor Early Paleozoic rocks)**

15 HOLYROOD INTRUSIVE SUITE: *granite (U-Pb zircon age 620 $^{+2.2}_{-1.7}$ Ma*)*

14 DOGBERRY HILL GABBRO: *fine- to coarse-grained massive gabbro (age of intrusion uncertain)*

**SIGNAL HILL GROUP (Units 9 to 13)**

12, 13 FLAT ROCK COVE FORMATION (13): *red and grey sandstone, siltstone, mudstone, conglomerate and breccia.* **13a,** Knobby Hill Member: *grey conglomerate and sandstone;* **13b,** Piccos Brook Member: *locally derived breccia and red muddy sandstone.* BLACKHEAD FORMATION (12): **12a,** Petty Harbour Member: *red sandstone and granule conglomerate;* **12b,** Maddox Cove Member: *red mudstone and sandstone; minor tuff;* **12c,** Spriggs Point Member: *red sandstone and mudstone (lower part); greenish-grey, red and white sandstone and mudstone (upper part);* **12d,** Deadman's Brook Member: *green mudstone and sandstone;* **12e,** Cliff Point Member: *red and green sandstone, siltstone and mudstone*

11 CUCKOLD FORMATION: *red conglomerate and sandstone.* **11a,** Cabot Tower Member: *medium- to coarse-grained red sandstone and interbedded red pebble conglomerate;* **11b,** Cape Spear Member: *red pebble to cobble conglomerate and coarse-grained red sandstone; contains exotic clasts;* **11c,** Skerries Bight Member: *pebble conglomerate, passing into coarse grained red sandstone at top*

10 QUIDI VIDI FORMATION: *red and green sandstone, siltstone and mudstone; minor pebble conglomerate and intraformational breccia*

9 GIBBETT HILL FORMATION: *thick bedded, greenish-grey sandstone, siltstone and tuff; minor red sandstone and siltstone and greenish-grey conglomerate*

**ST. JOHN'S GROUP (Units 6 to 8)**

8 RENEWS HEAD FORMATION: *thin, lenticular bedded, dark-grey sandstone and minor shale*

7 FERMEUSE FORMATION: *grey to black shale containing thin lenses of buff-weathering sandstone and siltstone; mainly light grey, thinly bedded, contorted shale and sandstone near base (slumped and resedimented beds)*

6 TREPASSEY FORMATION: *medium- to thin-bedded, graded, grey sandstone and shale; minor tuffaceous rocks*

**CONCEPTION GROUP (Units 4 and 5)**

5 MISTAKEN POINT FORMATION: *medium bedded, grey to pink sandstone and green to purple and red shale, minor thin tuff horizons; contains Precambrian fossils.* **5a,** Middle Cove Member: *medium bedded, greenish-grey and red siliceous siltstone and tuffaceous sandstone; contains Precambrian fossils; gradational into Mannings Hill Member. Includes* **5m,** *a distinctive marker unit of red, waterlain tuff and white vitric tuff;* **5b,** Hibbs Cove Member: *red and green tuffaceous siltstone and sandstone; contains Precambrian fossils; gradational into Trepassey Formation*

4 DROOK FORMATION: *green siliceous siltstone and sandstone, silicified tuff, grey, coarse grained turbiditic sandstone.* **4ax,** Octagon Pond Member: *grey to bluish-green chert, (stratigraphic position uncertain; possible equivalent of Broad Cove River Member);* **4a,** Broad Cove River Member: *thickly bedded chert and volcaniclastic sandstone;* **4b,** Bauline Line Member: *grey disorganized conglomerate (mixtite), green silty sandstone, red mixtite at top;* **4c,** Torbay Member: *red and green, medium- to coarse-grained, parallel- to streaky-laminated sandstone;* **4d,** Mannings Hill Member: *white to yellowish-green weathering, thickly bedded, siliceous sandstone; minor units of greenish-grey, thin- to medium-bedded siltstone and graded sandstone; minor tuff*

**HARBOUR MAIN GROUP (Units 1 to 3; not listed in stratigraphic order)**

3 PORTUGAL COVE FORMATION: *green siliceous sandstone and chert; minor red sandstone, siltstone, argillite and chert*

2 PRINCES LOOKOUT FORMATION: *massive and pillow basalt:* **2a,** Blast Hole Ponds Unit; *metabasalt and tuff*

1 ST. PHILLIPS FORMATION: *green metatuff, agglomerate, mafic lava; siliceous volcaniclastic sedimentary rocks; includes rhyolitic and gabbroic to diabasic intrusive rocks:* **1a,** Beachy Cove Member: *strongly deformed and disrupted beds of basalt, rhyolite, tuff, agglomerate, massive arkosic sandstone, argillite, chert; includes rhyolitic and gabbroic to diabasic intrusive rocks*

| FAULTS | |
|---|---|
| DHF | Dogberry Hill Fault |
| DF | Donovans Fault |
| FRT | Flat Rock Thrust |
| FPF | Freshwater Pond Fault |
| KRF | Kenmount Road Fault |
| MRF | Main River Fault |
| MPF | Millers Pond Fault |
| OPF | Ocean Pond Fault |
| NF | Newtown Fault |
| PCF | Portugal Cove Fault |
| RHCF | Red Head Cove Fault |
| SCF | Shoe Cove Fault |
| WFZ | Waterford Fault Zone |
| WPF$^{\Delta}$ | Wedgewood Park Fault |
| WHRF$^{\Delta}$ | Witch Hazel Road Fault |

| FOLDS | |
|---|---|
| BHS | Blackhead Syncline |
| BPS | Bremigins Pond Syncline |
| CPA | Cochrane Pond Anticline |
| GDS | Glendale Syncline |
| KHA | Kenmount Hill Anticlinorium |
| KHS | Knobby Hill Syncline |
| MCA$^{\Delta}$ | Middle Cove Anticline |
| NPD$^{\Delta}$ | Newfound Pond Dome |
| PPA | Paddys Pond Anticline |
| PS | Paradise Syncline |
| PPD | Pippy Park Dome |
| SPS$^{\Delta}$ | Snegge Point Syncline |
| TD | Torbay Dome |
| WIPB | Western Island Pond Basin |
| WLB | Windsor Lake Basin |

Δ Minor faults and folds

References: * Krogh *et al.*, 1983

The base of the group is not exposed in the Avalon Zone of Newfoundland and it is presumed to be underlain by continental gneissic basement (O'Brien *et al.*, 1983). In the central and southern Avalon Peninsula, the group is considered to be unconformably overlain by the Conception Group (Rose, 1952; McCartney, 1967; Williams and King, 1979), although examples of interfingering have also been described (Hughes and Brückner, 1971; Williams and King, 1979).

Isotopic studies by Krogh *et al.* (1983, 1988) suggest that the concept of the Harbour Main Group as a single stratigraphic unit may require revision; various isotopic determinations and estimates of the absolute age of the volcanic rocks range from 525 Ma to greater than 800 Ma. Krogh *et al.* (1988) document a period of igneous activity within the Harbour Main Group spanning at least 45 million years. Rocks presently included in the Harbour Main Group, with ages of 585 Ma or less, may be partially related in time to the Bull Arm Formation of the western Avalon Peninsula; both volcanic units are mildly alkalic to tholeiitic (King and O'Brien, in press).

## Local Distribution, Origin, Thickness and Division

Pillow basalt, and metavolcanic and metasedimentary strata of the Harbour Main Group, underlie about 25 km$^2$ of the map area, and form the prominent coastal range east of Conception Bay (Figure 7). Much of the sequence was formed in a deep-marine environment, in contrast to the typical subaerial depositional environments represented in the type locality. The rocks have been brought up along bifurcations of the Topsail Fault and are distributed in two mutually opposing, wedge-shaped blocks that taper toward Portugal Cove. The base of the group is not exposed and the boundary with the Conception Group is interpreted as gradational. The scarcity of facing criteria, coupled with complex internal structure, including repetition by intense folding and faulting, make thickness estimates impractical. However, despite the structural complexities, the Harbour Main Group is divided into three distinctive mappable formations, each showing some degree of internal lithic homogeneity or lithic heterogeneity.

## St. Phillips Formation (Unit 1)

### *Name, Distribution and Thickness*

The name St. Phillips Formation is here formally proposed for the mainly green to grey pyroclastic rocks exposed between Portugal Cove and Topsail Head. The formation occurs as a wedge-shaped belt, which is up to 2 km wide. It is well exposed along the coast, but with the exception of incised river valleys and roadcuts inland exposures are scarce. The type locality extends from lower Broad Cove River (250 m due west of survey station # 026676) to northeast Broad Cove, St. Phillips, a distance of 1.4 km. The formation continues under Conception Bay and is assumed to extend to the Topsail Fault. Thickness estimates are not possible due to the obliteration of bedding by cleavage and the lack of an exposed top or bottom.

### *Lithology*

The St. Phillips Formation is relatively homogeneous in contrast with the Portugal Cove Formation. It typically consists of light-green phyllitic tuff and agglomerate intercalated with minor units of red mudstone, grey to white siliceous sandstone and mafic lava ('greenstone'). The tuffs are associated with strongly deformed, siliceous sedimentary rocks and mafic volcanic rocks (Beachy Cove Member) along the eastern coast of Conception Bay.

### *Structural Relations*

The formation is strongly cleaved with near vertical to steep (70 to 85°) west to northwest dips. Tectonically stretched tuff clasts define down-dip cleavage lineations, with superimposed east–west slickensides, suggesting high-angle thrusting followed by strike-slip deformation of the unit. The eastern margin of the formation is defined by the Dogberry Hill Fault, which extends from Portugal Cove to Three Island Pond where it joins the Topsail Fault. The western margin of the formation below Topsail Head is defined by the Topsail Fault, which brings it in contact with deformed Lower Cambrian strata.

### *Correlation*

The St. Phillips Formation may be, in part, a correlative of the Portugal Cove Formation. Apart from rare relict pillow structures, the St. Phillips Formation is lithologically unlike the Princes Lookout Formation; it may, however, represent a penecontemporaneous volcanogenic lithofacies.

#### *Beachy Cove Member (Subunit 1a)*

*Name, Distribution and Lithology.* Between the headland at the southwestern end of Portugal Cove and Beachy Cove, and intermittently along the coast to St. Thomas, green phyllitic tuff (St. Phillips Formation) is interspersed with strongly deformed and disrupted beds of siliceous siltstone and sandstone. These rocks are intruded by numerous felsic and mafic dykes and sills, which are also sheared; the entire assemblage now occurs as irregular to lozenge-shaped blocks with a foliation, parallel to the regional cleavage. This specially developed part of the St. Phillips Formation is well exposed at Beachy Cove and is here formally named the Beachy Cove Member.

*Correlation.* The strongly deformed siliceous sedimentary rocks and metatuff, which form the headland of southwest Portugal Cove, are comparable with those of the Portugal Cove Formation on the north side of the cove. The Beachy Cove Member is therefore probably an extension of the Portugal Cove Formation, although it should be emphasized that the latter unit lacks the green phyllitic tuff characteristic of the St. Phillips Formation. If the Dogberry Hill Fault is a continuation of the Freshwater Pond Fault (which at present is uncertain), then the two geographically separate units are probably correlative.

## Princes Lookout Formation (Unit 2)

### *Name, Distribution and Thickness*

The name Princes Lookout Formation is here formally proposed for the formation of massive- and pillow-basalt flows that are well exposed in the vicinity of Princes Lookout, a prominent hill readily accessible by road to the east of Portugal Cove. The formation occurs within a 0.5-to 2-km-wide fault-bounded belt that has a north-northeast trend (Figure 7). It extends northward beyond the map area; southward, the Dogberry Hill Fault brings it in contact with the St. Phillips Formation at Beachy Cove Brook. The type locality is 1 km due south of Portugal Cove (Plate 12) and is defined on the hill summit by a geodetic survey monument (# 029005, map sheet 0252). Several trails lead to the site from Neary's Pond (shown as Piccos South Pond on map sheet 0252).

**Plate 12.** *Type locality of Princes Lookout Formation, exposed in fault scarp south of Portugal Cove. Boundary with Drook Formation in upper right.*

An access road to Blast Hole Ponds (Anglican Cemetery Road) provides a readily accessible reference section across the formation. Woods roads commencing on the Bauline Line provide access to the northern part of the volcanic belt. A thickness of at least 250 m occurs in some sections, but this may include structural repetition of some flows.

### *Lithology*

Mafic flows are best exposed in the type locality and on numerous other hill summits. Dark grey and black flows of basaltic pillow lava are abundant and together with more massive flows, comprise about 95 percent of the formation. Individual pillows are well developed as ellipsoidal to spherical blocks, ranging from 0.2 to 2 m in diameter, and display epidotized and often radially cracked skins. The rock is fine grained and consists predominantly of acicular to lath-like sodic plagioclase (albite–oligoclase) with minor clinopyroxene set in an altered matrix of chlorite, epidote, hematite and magnetite. Irregular stringers and veinlets of epidote and chlorite are present. Vesicles and amygdules are conspicuous in some flows.

Narrow discontinuous units of mafic aquagene tuff are commonly associated with the pillow lava and are considered to have formed by nonexplosive granulation. Thin beds of distinctive green and red siliceous argillite, siltstone, and very fine grained sandstone, occur sporadically throughout the formation and locally display grading, cross-lamination and slumping. Red to purple, oxidized flow-top basaltic breccias are common, particularly along the eastern margin of the formation northeast of Portugal Cove and along the western margin west of Princes Lookout.

### *Chemistry*

Chemically, the pillow basalt (Table 3, Analysis 2) resembles the hawaiite (Table 3, Analysis 3) of Macdonald

**Table 3:** Chemical analyses of basic lavas of the Harbour Main Group, compared with Hawaiite

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 59.45 | 48.60 | 48.60 | 50.88 | 54.50 |
| $Al_2O_3$ | 17.51 | 15.26 | 16.49 | 18.86 | 15.84 |
| $Fe_2O_3$ | 1.58 | 6.13 | 4.19 | 6.17 | 3.81 |
| FeO | 3.68 | 4.44 | 7.40 | 3.47 | 5.08 |
| MgO | 3.54 | 6.84 | 4.70 | 5.86 | 5.53 |
| MnO | 0.09 | 0.21 | 0.18 | 0.11 | 0.12 |
| CaO | 2.58 | 8.06 | 7.79 | 6.74 | 4.11 |
| $Na_2O$ | 7.42 | 4.37 | 4.43 | 4.74 | 6.58 |
| $K_2O$ | 1.44 | 0.84 | 1.60 | 1.19 | 0.14 |
| $TiO_2$ | 0.67 | 1.48 | 3.16 | 1.66 | 1.40 |
| $P_2O_5$ | 0.13 | 0.21 | 0.69 | 0.32 | 0.28 |
| $CO_2$ | | | 0.04 | | |
| $H_2O+$ | | | 2.23 | | |
| $H_2O-$ | | | 0.19 | | |
| L.O.I. | 2.20 | 3.06 | | | |
| Total | 100.29 | 99.50 | 99.23 | 100.00 | 99.85 |

L.O.I. : loss on ignition

1. Metapillow basalt, Blast Hole Ponds Unit, 0.75 km due south of Ocean Pond, Bauline. Sample: AK85-1241 (47°39'55"N, 52°50'15"W). Analysis: Mineral Development Division.
2. Pillow basalt, Princes Lookout Formation, 1.62 km due north of Northeast Pond, Portugal Cove. Sample: AK85-1253 (47°39'15"N, 52°50'00"W). Analysis: Mineral Development Division.
3. Average hawaiite, Hawaii (Macdonald and Katsura, 1964, Table 10/5).
4. Average of 3 basic lavas (hawaiite–mugearite) west of Colliers Bay (Papezik, 1970; Table IV A). Recalculated to 100% without $H_2O$ and $CO_2$.
5. Mugearite flow, top of ridge 2 km south of Cape St. Francis lighthouse (Papezik, 1970; Table 1, No. 18).

and Katsura (1964). The mafic flows appear to be chemically similar to rocks considered by Papezik (1970) to be of the hawaiite–mugearite-type present in the Harbour Main volcanic belt, west of Colliers (Table 3, Analysis 4). In contrast, pillow basalts from Cape St. Francis are marginally higher in their silica and soda content (Table 3, Analysis 5). Preliminary studies of trace-element patterns for the Princes Lookout Formation, indicate the basalts may have been altered by alkaline metasomatism (Figure 8).

### *Structural Relations*

The internal structure of the Princes Lookout Formation is uncertain. Minor clastic units, especially the red argillite beds in the basalt, exhibit open to tight northeast trending folds. Stratigraphic top determinations in the clastic units and pillows indicate much of the eastern margin of this belt, which is steeply dipping to the west, is overturned. The presence of lower Conception Group strata to the northwest and southeast of Princes Lookout, suggests that the formation occupies either a horst or possibly an antiform.

The western margin of the Princes Lookout Formation, to the north of Portugal Cove, coincides with the Freshwater Pond Fault but along low ground, east of Portugal Cove, the precise contact with green siliceous siltstones of the Conception Group is unexposed. Tight, disrupted folds and steep northwesterly dipping cleavage in both units indicate shearing but the amount of displacement is uncertain. Similar relationships occur along the eastern margin. Intense brecciation of Conception siltstones at several localities north-northeast of Piccos Pond suggest a fault contact.

### *Correlation*

Massive and pillow flows of the Princes Lookout Formation are exposed at several localities near the Bauline Road–Bauline Line junction (approximately 2 km east of Ore Head). Its northward extension beyond this is uncertain due to extensive organic terrain. A large exposure of pillow basalt between Miles and Grog ponds (about 4 km north, northeast of the road junction) may be a possible correlative. Comparable pillow basalts occur in the Cape St. Francis area. The formation may also be related in time to the mafic flows (hawaiites and mugearites) of Colliers Bay.

#### *Blast Hole Ponds Unit (Subunit 2a)*

A wedge-shaped fault-block of polyphase deformed metavolcanic rock (greenstone) to the north of Blast Hole Ponds (2 km north-northeast of Portugal Cove) is considered an extension of the Princes Lookout Formation and is here informally termed the Blast Hole Ponds Unit. It has been traced to Ocean and Freshwater ponds where it has an exposed width of 750 m. A possible southward extension occurs as a small 'exotic' fault block of chlorite schist, immediately north of the ferry landing at Portugal Cove.

In this lithotectonic unit, pillows and associated tuffs, red agglomerate, breccias and argillites, are intensely sheared, tectonically flattened and foliated; traces of pillow structure persist on weathered outcrops (Plate 13). Thin beds of red argillite show polyphase folding. Chemical analysis of the altered basalt indicates comparatively high silica and soda values (Table 3, Analysis 1; Figure 8), in comparison with fresh pillow basalts from Princes Lookout and Cape St. Francis.

The unit is separated from the Portugal Cove Formation to the west by a narrow shear zone, the Ocean Pond Fault; the amount of displacement along this fault is uncertain. A 250-m-wide shear zone, the Freshwater Pond Fault, separates the member from fresh pillow basalts (Princes Lookout Formation) to the east. Boudins and sheared sill-like intrusions of coarse grained to pegmatitic granite occur in the highly sheared greenstone within the Freshwater Pond Fault zone; examples may also be seen in the 'exotic' fault-block, north of the ferry landing at Portugal Cove. The age of the granitoid rocks and their affinities with the Holyrood Intrusive Suite (Unit 15 in Figure 7) are uncertain.

## Portugal Cove Formation (Unit 3)

### *Name, Distribution and Thickness*

The name Portugal Cove Formation is here formally proposed for the strongly deformed assemblage of mainly siliceous, volcaniclastic sandstone and siltstone, and mafic pyroclastic rocks, which form the high hills to the north of the breakwater at Portugal Cove (Plate 14). It occurs as a narrow belt (up to 1 km wide) to the west of the Princes Lookout Formation. In the type section, a minimum thickness of about 250 m is exposed on the west limb of a synform (to the northwest of survey monument # 029028, map sheet 0252). This structure is disrupted by several northwest trending strike-slip faults, including the Main River Fault.

The Portugal Cove Formation is well exposed to the north of the type section, on the high ground between Blast Hole Ponds and Ore Head, and along the steep coastal cliffs beyond the northwestern boundary of the map area (Figure 7). Although the northern part of the belt is most representative of the formation, access is difficult on foot; the readily accessible type locality, with its structural complications, is therefore supplemented by a composite stratotype consisting of reference sections crossing the formation about 1 km to the north and south of Brocks Pond (latitudes 47°39.6' and 47°40.7'N).

Tectonic repetition of units, together with the unknown submarine extent of the formation below Conception Bay, make maximum thickness estimates impossible; the minimum thickness is at least 500 m.

### *Lithology*

The Portugal Cove Formation, including the various igneous rocks present, shows lithic heterogeneity, which in itself constitutes a form of unity when compared with other

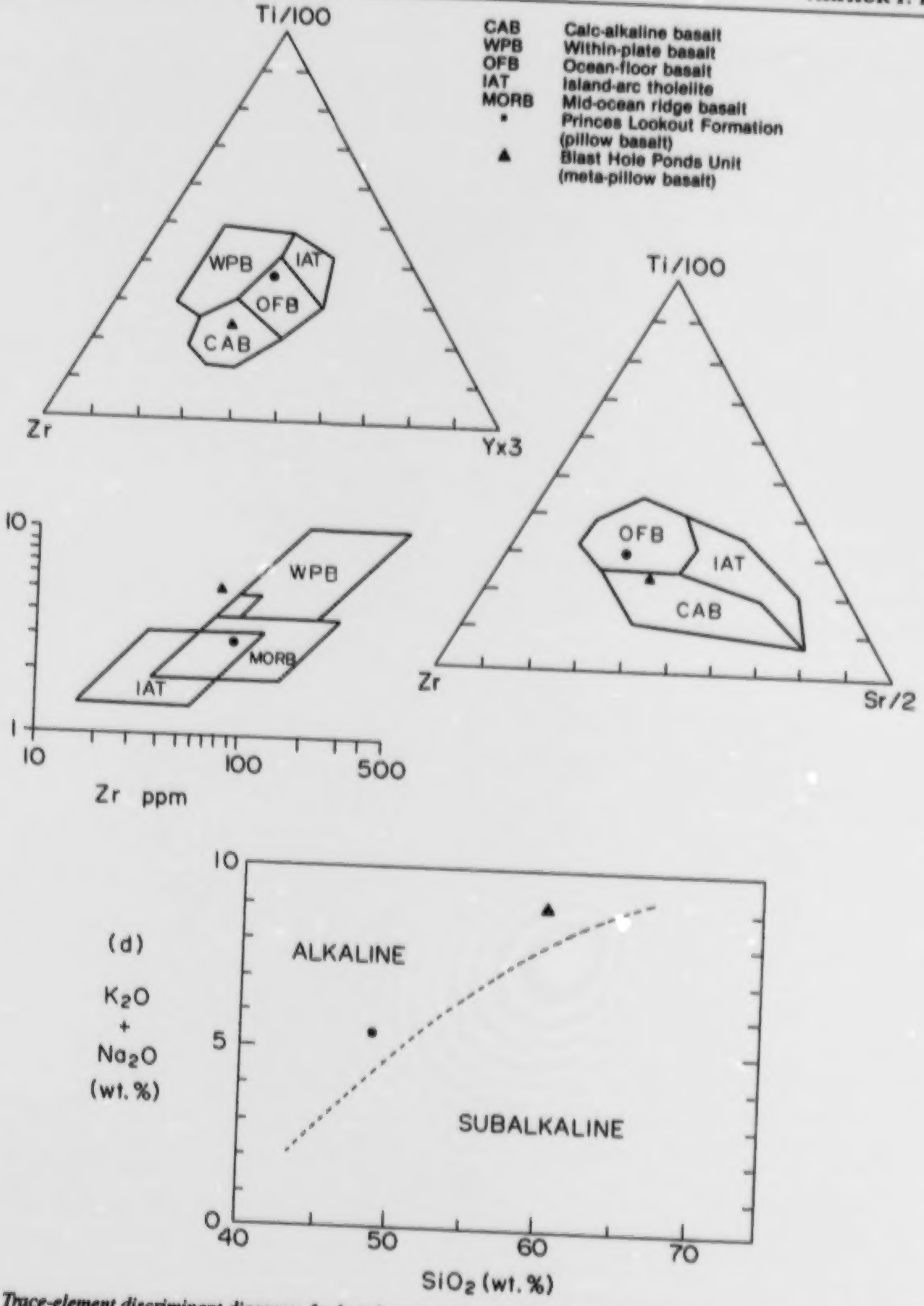


**Figure 8.** *Trace-element discriminant diagrams for basalt samples from Princes Lookout Formation, Harbour Main Group. Zr/Y-Zr plot after Pearce and Norry (1979); Ti-Zr-Y diagram after Pearce and Cann (1973); $K_2O+Na_2O-SiO_2$ plot after Irvine and Baragar (1971).*

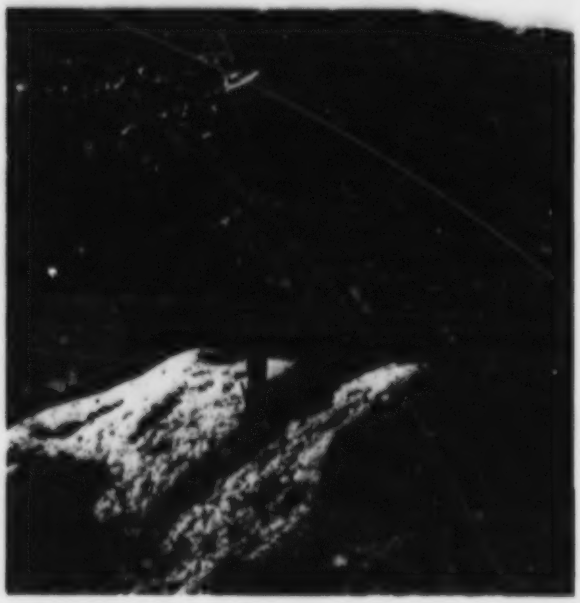


**Plate 13.** *Tectonically flattened basaltic pillow lava (Blast Hole Ponds Unit) with individual blocks up to 2 m diameter and 0.5 m in width. Prominent valley defines Ocean Pond Fault and separates unit from Portugal Cove Formation to the west (i.e., upper part of plate).*

rock units in the map area. It consists of a strongly deformed assemblage of epiclastic sedimentary rocks interbedded with mafic tuffs and minor flows of rhyolite and basaltic pillow lava. Clasts of reworked mafic and felsic volcanic rocks and sedimentary detritus are tectonically flattened and appear to be stretched in a down-dip direction. Throughout much of the formation, mafic tuffaceous units and shales were metamorphosed to pelites. The assemblage is intruded by numerous sills, dykes and stocks of rhyolite, quartz diorite, granite, diabase and gabbro, most of which show weak to strong northerly trending foliation parallel to the regional cleavage.

The main sedimentary rock types in the type section include white, grey, and green siliceous, volcaniclastic sandstone, siltstone and chert; minor black shale, red to black agglomerate, scoriaceous pebble conglomerate and oxidized mafic breccia are exposed near Brocks Pond. The sedimentary rocks of the formation are generally well bedded and medium to thick beds predominate. Turbiditic sandstones are common and show grading, small-scale cross-lamination, flattened sole marks, flame structures and rip-up clasts. Some sandstone–shale and tuff units are arranged in distinctive, 2- to 10-m-thick thinning-upwards cycles; alternating coarse–fine units are characteristic of the formation between Blast Hole and Brocks ponds. Conglomerate, agglomerate and breccia occur locally. In the northern part of the map area, volcanic and intrusive rocks form an important component of the formation between Brooks and Hickey's ponds (Subunit 3a).

### *Structural Relations*

The internal structure of the Portugal Cove Formation is complex as a result of polyphase deformation. Intense repetition by imbricate folding and faulting is widespread and may be seen immediately north of the Portugal Cove breakwater. Tectonic emplacement of various rock units by steeply northwest-dipping thrust faults is characteristic of the formation throughout the map area. The major structure between Portugal Cove and Brocks Pond appears to be a series of tight to isoclinal antiforms and synforms having steeply dipping, disrupted limbs. North-northeast-trending cleavage has a near vertical to a high-angle westward dip.

The Portugal Cove Formation is separated from the Blast Hole Ponds Unit by a narrow shear zone, the Ocean Pond Fault. Between the three Blast Hole Ponds, the two stratigraphic units appear to merge although a precise contact was not observed. The formation is separated from the Princes Lookout Formation further south by the Freshwater Pond Fault.

North of Portugal Cove, the Freshwater Pond Fault is intersected by the northwest-trending Main River Fault, a sinistral strike-slip fault having an oblique-slip component. Metasedimentary rocks on the northeast side of the cove are in fault contact with the Princes Lookout Formation; they are unlike those of the Portugal Cove Formation and are correlated with the Bauline and Torbay members of the Conception Group. The Portugal Cove Fault, interpreted as a major thrust fault (R.S. Smith and T. Calon, personal communications, 1987), separates the Portugal Cove Formation, in the type locality, from the presumed Conception Group metasedimentary rocks to the east; this fault is possibly an extension of the Ocean Pond Fault.

### *Correlation and Stratigraphic Implications*

The Portugal Cove Formation at its type locality resembles the highly deformed, lower Conception Group sandstones above the Flat Rock Thrust in southwestern Torbay Bight. However, they differ in that the former has a higher percentage of mafic tuff. In the southern Avalon Peninsula, the Biscay Member of the cherty, Drook Formation consists of two thin, mafic volcanic horizons (Williams and King, 1979), but lacks mafic tuff bands.

The distribution of the Portugal Cove Formation generally coincides with Map Unit 3 of Hsu (1975), as does the St. Phillips Formation. Hsu's (1975) map shows this unit (Map Unit 3) extending as a narrow belt along the coastal range to Cape St. Francis, where it is associated with pillow basalt (Map Unit 3a, Hsu, 1975). Preliminary aerial and ground reconnaissance studies (by the writer) indicate that the Portugal Cove Formation continues northward from Ocean Pond as a narrow (up to 1 km wide) belt to Pouch Cove Northwest Pond. Epiclastic sedimentary rocks interbedded with thick mafic flows and tuffs on the coast at Bear Cove, 2 km south-southeast of Cape St. Francis lighthouse, are presumed correlatives.

**Plate 14.** *Tightly folded and disrupted volcaniclastic sandstones of Portugal Cove Formation in the type locality.*

The stratigraphic position of the Portugal Cove Formation is uncertain because of intense structural deformation. Both Rose (1952) and Hsu (1975) have included these rocks within the Harbour Main Group. However, epiclastic sedimentary rocks that comprise most of this formation, are comparable with the lower part of the Conception Group present in the map area, but the presence of abundant mafic tuff beds and minor rhyolite and basalt flows, supports the inclusion of the formation within the volcanogenic Harbour Main Group. It is therefore suggested that the Harbour Main Group and the lower part of the Conception Group in the St. John's map area are largely penecontemporaneous. It is noteworthy that comparable relationships occur between the Love Cove and Connecting Point groups of Bonavista Bay (O'Brien and Knight, 1988).

## CONCEPTION GROUP (UNITS 4 and 5)

### Definition

The Conception Group (Rose, 1952) occurs throughout the Avalon Peninsula and is dominated by green to grey siliceous sedimentary rocks (Figure 3). It also includes conglomerate, tuff, agglomerate, tillite, minor mafic pillow lava, orthoquartzite and mafic dykes. The general distribution of Conception Group rocks, within the Avalon Peninsula, is shown on the regional maps of Rose (1952), McCartney (1967), Hsu (1975), Williams and King (1979) and King (1988).

A complete section of the Conception Group is not exposed on the Avalon Peninsula. Rose (1952) informally divided the Conception Group into the Conception Slate and Torbay Slate (names originally introduced by Walcott, 1899) but did not define their regional boundaries nor did he designate a formal type locality for the group. Brückner (in King *et al.*, 1974) compiled a regional map of Conception Group rocks, based on his own observations and on detailed studies by Memorial University of Newfoundland students. Hsu (1975) subdivided the Conception Group north of Windsor Lake into three informal lithostratigraphic divisions: a lower arkosic sandstone unit, a tilloid, and an upper unit of greywacke, siltstone, shale, chert and minor tuff; only the upper unit is shown on his map of the St. John's Peninsula extending southward from Windsor Lake into the Kenmount Hill–Mt. Pearl area. Williams and King (1979) divided the Conception Group of southeastern Avalon Peninsula into five formations, Mall Bay, Gaskiers, Drook, Briscal and Mistaken Point, two of which have wide regional extent and may be important in global stratigraphic correlations; a distinctive tillite unit up to 300 m thick (Gaskiers Formation), occurs near its base and tuffaceous sandstones with well-preserved metazoan fossils (Mistaken Point Formation) occur at its top (Figure 6). They designated the Trepassey region as the type area of the Conception Group.

The abundance of tuff and other volcanic detritus throughout the estimated 3- to 5-km-thick marine sequence, suggests sedimentation contemporaneous with volcanism, and perhaps, as suggested by Hughes and Brückner (1971), related

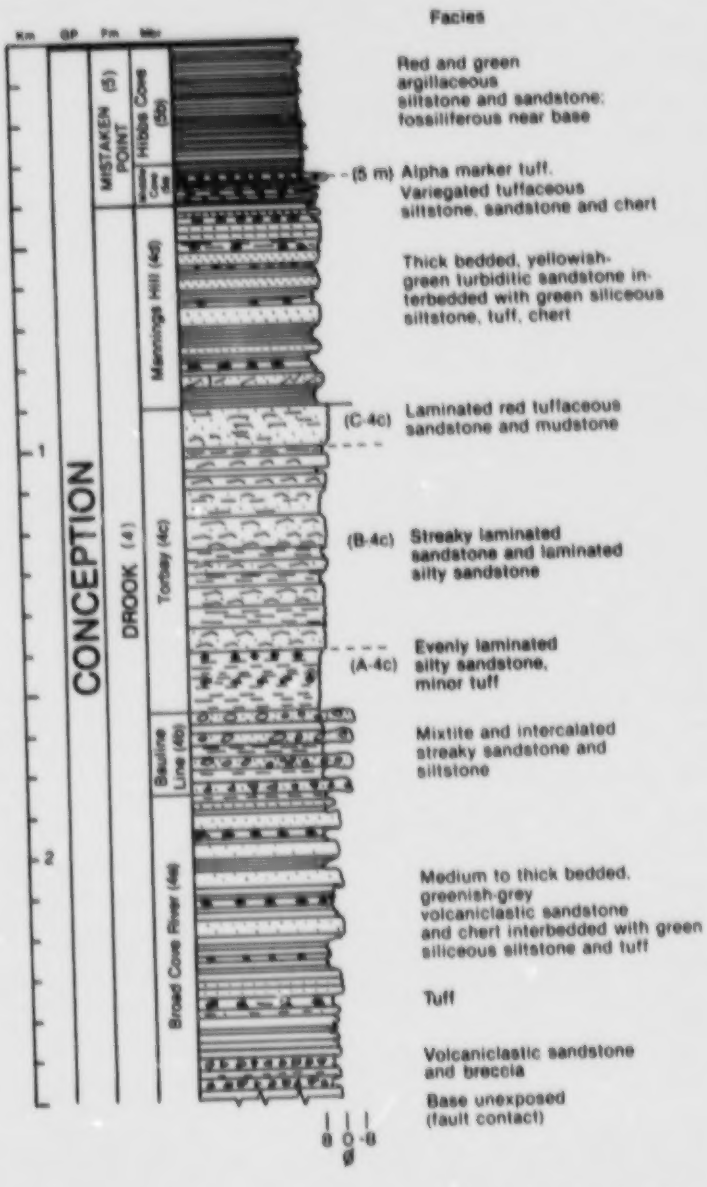

Facies
Km
GP
Fm
Mbr
1
2
CONCEPTION
MISTAKEN POINT (5)
DROOK (4)
Hibbs Cove (5b)
Mannings Hill (4d)
Torbay (4c)
Bauline Line (4b)
Broad Cove River (4a)
Red and green argillaceous siltstone and sandstone; fossiliferous near base
(5 m) Alpha marker tuff.
Variegated tuffaceous siltstone, sandstone and chert
Thick bedded, yellowish-green turbiditic sandstone interbedded with green siliceous siltstone, tuff, chert
(C-4c) Laminated red tuffaceous sandstone and mudstone
(B-4c) Streaky laminated sandstone and laminated silty sandstone
(A-4c) Evenly laminated silty sandstone, minor tuff
Mixtite and intercalated streaky sandstone and siltstone
Medium to thick bedded, greenish-grey volcaniclastic sandstone and chert interbedded with green siliceous siltstone and tuff
Tuff
Volcaniclastic sandstone and breccia
Base unexposed (fault contact)
8
0
-8
ø

**Figure 9.** *Composite stratigraphic section of the Conception Group.*

in time to the Harbour Main Group volcanism. The basal part of the Conception Group is older than the 620 Ma (Krogh *et al.*, 1983) Holyrood Intrusive Suite, although a U–Pb zircon date of 565 ± 3 Ma (G. Dunning, personal communication, 1987) on the youngest beds (Benus, 1988) indicates that the group was formed over a period of 60 Ma or more.

## Local Distribution, Thickness and Division

Conception Group rocks form the backbone of the St. John's Peninsula and comprise about 60 percent of the map area. The group crops out in a 12-km-wide belt between the coastal ranges; it is transitional into the Harbour Main Group in the west and underlies the St. John's Group in the east. It is separated by an angular unconformity, the 'Lilly Unconformity' (Anderson *et al.*, 1975), from the Signal Hill Group, northeast of St. John's. Two formations of the Conception Group, the Drook and Mistaken Point, occur within the map area. No complete section of the group is exposed and folding and faulting preclude accurate measurement of thickness. The estimated exposed thickness is 2.6 km. A composite stratigraphic section of the Conception Group within the map area is shown in Figure 9.

## Drook Formation (Unit 4)

### *Name, Distribution and Thickness*

Green, siliceous volcaniclastic sedimentary rocks of the Drook Formation (Williams and King, 1979) constitute much of the Conception Group throughout the Avalon Peninsula. In the type locality of the southern Avalon Peninsula, the Drook Formation contains argillaceous chert, siliceous siltstone, sandstone, and silicified tuff. It is conformably overlain by coarse-grained thick-bedded sandstones of the Briscal Formation, which are conformably overlain by tuffaceous shales and sandstones of the Mistaken Point Formation (Figure 6). The Drook Formation conformably overlies the Gaskiers Formation in eastern St. Mary's Bay (Figure 3). Williams and King (1979) calculated a minimum estimated thickness of 1500 m, but because of its complicated structure and lack of exposure, the actual thickness is not known.

The Drook Formation is the most extensive and thickest unit in the map area. The various members of the formation are relatively competent rocks, which form large-scale domes and basins, corresponding with areas of topographic high and low relief. The maximum exposed thickness along Broad Cove River is 2200 m, although 1500 m is generally the average throughout the map area. The Paddy's Pond and Cochrane Pond anticlines provide the longest and most complete cross-sections through the Drook Formation on the Avalon Peninsula (Figure 7); the formation there had an exposed thickness of about 1000 m before continuous roadcuts along the Trans-Canada Highway were either removed or covered.

The Drook Formation has been subdivided into five new members. They are described in ascending order.

### *Broad Cove River Member (Subunit 4a)*

*Name, Distribution and Thickness.* Medium- to thick-bedded, greenish-grey chert and coarse grained, volcaniclastic sandstone are exposed in Broad Cove River, northeastern Conception Bay. The type section of the proposed member commences at the junction of the Rainbow River and the Broad Cove River, above Dogberry Hill bridge (350 m west of survey monument # 026674, map sheet 0252), and carries on for about 900 m downstream (250 m west of survey monument # 026676). Its exposed stratigraphic thickness is estimated at 750 m.

The member forms part of the steeply eastward dipping limb of the Paradise Syncline. It appears to maintain uniform thickness between Adams Pond (Paradise) and the type section. The width of the member along Witch Hazel Road, 3 km north of the type section, is about 1250 m; this apparent thickness is due to tectonic repetition of the unit. The member defines a series of major flexures in the vicinity of Beachy Cove and Neary's Pond. It is poorly exposed between Neary's Pond and the Bauline Road.

*Lithology.* Thick bedded greenish-grey cherts are characteristic of the Broad Cove River Member (Figure 9). They are dense, impure, siliceous rocks composed of microcrystalline quartz with isolated traces of silt to fine sand-size grains of quartz, plagioclase (albite–oligoclase) and minor zircon. Rock fragments, consisting of angular chips (1 to 2 mm) of rhyolite, mafic tuff, basalt and occasionally granophyre are present mainly towards the base of the succession. Outlines of shards are present and are best observed under low-intensity plane-polarized light.

Medium- to coarse-grained volcaniclastic sandstones are commonly interbedded with the cherts. They have a variable composition and range from lithic sandstone, to arkose to orthoquartzite. Lithic or tuffaceous sandstone predominate; they contain angular to subrounded grains of quartz and feldspar (twinned albite, perthite), broken shards of volcanic glass, and abundant small fragments of rhyolite, with minor basalt and rare aplite and micropegmatite. The arkosic sandstones contain over 25 percent plagioclase (albite), variable amounts of detrital quartz and minor rhyolitic and basaltic fragments. Orthoquartzites with rounded grains of quartz occur as thin laminae in the upper part of the formation. All sandstones show at least some degree of silicification. Flute, groove and prod marks are present but are seldom adequately exposed for paleocurrent analyses.

Thinly bedded units of graded siliceous siltstones are locally interbedded with the cherts and sandstones. They more commonly occur as a thin veneer above fining-upward sandstones. Silty sandstones show parallel, convolute and cross-laminations as well as graded bedding.

*Structural Relations.* Although the base of the Broad Cove River Member is unexposed, the presence of tuff as well as rip-up clasts of tuff and lava in the lowermost beds suggests that this unit overlies the Harbour Main Group. The Harbour Main–Conception contact is therefore presumed to be conformable and gradational. The cherts and sandstones are conformably overlain by the Torbay, and (locally) the Bauline Line members.

*Correlation.* The epiclastic sedimentary rocks of the Portugal Cove Formation (Harbour Main Group) are generally comparable in lithofacies with the Broad Cove River Member. The latter, however, lacks significant mafic volcanic horizons and is therefore interpreted as a transitional but stratigraphically higher unit.

Grey to green chert of the Octagon Pond Member is a possible equivalent of the Broad Cove River Member. Thick, disrupted beds of chert, immediately above the Flat Rock Thrust Zone at Torbay, may be equivalent to the lower part of the Torbay Member or the upper part of the Broad Cove River Member (Figure 10).

In the southern Avalon Peninsula, the Cape English and Peter's River members of the Drook Formation, are characterized by coarse, thick, grey sandstone beds up to 2 m thick that alternate with thin bedded, green cherts (Williams and King, 1979). These sections are facies equivalents of the Broad Cove River Member, although only an informal correlation can be made.

### *Octagon Pond Member (Subunit 4ax)*

*Name, Distribution and Thickness.* The name Octagon Pond Member, is proposed for the grey to sea-green cherts and thick-bedded siliceous sandstones, exposed between Octagon Pond and the town of Paradise in the southwestern part of the map area (Figure 7). The unit forms part of the moderately (25 to 40°) westward-dipping limb of the Paradise Syncline. A composite type-section is designated to include strata in the vicinity of the Paradise Road (between survey monuments #'s 026628 and 026638, map sheet 0255) and in a large quarry north of Brazil Pond. The estimated exposed stratigraphic thickness, including the quarry beds, is about 750 m.

*Lithology.* The rocks of the Octagon Pond Member are comparable with those of the Broad Cove River Member. Good examples of typical Octagon Pond chert occur northeast of Octagon Pond and opposite the Anglican Church, Paradise Road. The cherts are distinctive sea-green rocks having conchoidal fractures. They are silica rich rocks (Table 4, Analysis 6) chemically similar to vitric tuffs (Table 4, Analysis 4) near Middle Cove.

Medium- to thick-bedded sandstones and siltstones in the quarry, north of Brazil Pond, are not in exposed continuity with the cherts and are assumed to form the lower part of the member. Their present exposed thickness is about 250 m. Some silty beds contain abundant disseminated pyrite crystals giving fresh rock faces a rusty colour; they resemble pyrite-rich siltstones in the Middle Cove Member (Mistaken Point Formation), and pale green siltstones (Broad Cove

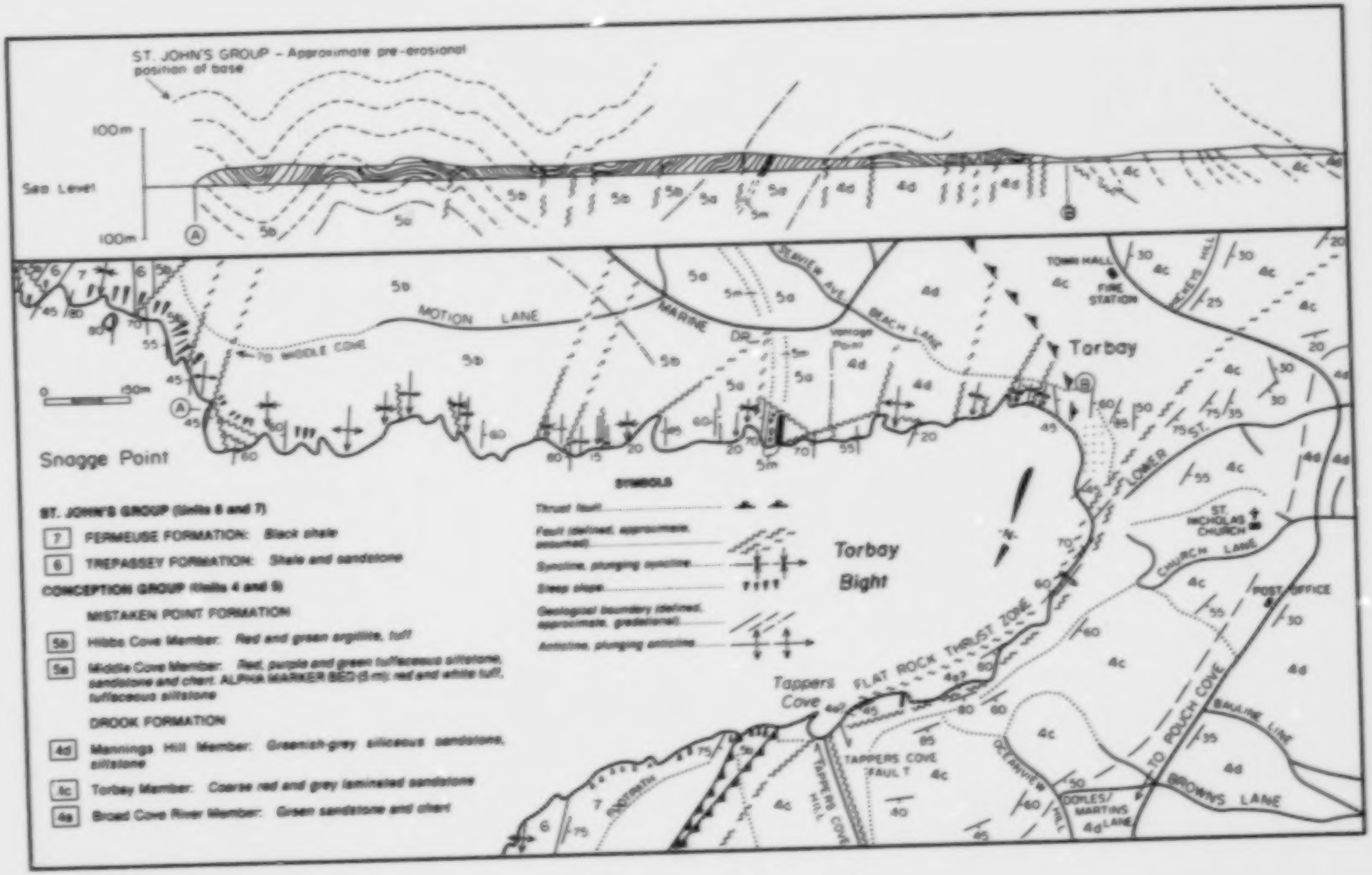

ST. JOHN'S GROUP - Approximate pre-erosional position of base
100m
Sea Level
100m
Ⓐ
Ⓑ
5a
5b
5m
4d
4c
Snogge Point
0
150m
MOTION LANE
TO MIDDLE COVE
MARINE DR.
SEAVIEW AVE.
BEACH LANE
Vantage Point
Torbay
TOWN HALL
FIRE STATION
PICKEYS HILL
LOWER ST.
ST. NICHOLAS CHURCH
CHURCH LANE
POST OFFICE
TO POUCH COVE
BAULINE LINE
BROWNS LANE
DOYLES/MARTINS LANE
OCEANVIEW HILL
TAPPERS COVE FAULT
TAPPERS COVE HILL
FOOTPATH
FLAT ROCK THRUST ZONE
Tappers Cove
Torbay Bight
N
SYMBOLS
Thrust fault
Fault (defined, approximate, assumed)
Syncline, plunging syncline
Steep slope
Geological boundary (defined, approximate, gradational)
Anticline, plunging anticline
ST. JOHN'S GROUP (Units 6 and 7)
7 FERMEUSE FORMATION: Black shale
6 TREPASSEY FORMATION: Shale and sandstone
CONCEPTION GROUP (Units 4 and 5)
MISTAKEN POINT FORMATION
5b Hibbs Cove Member: Red and green argillite, tuff
5a Middle Cove Member: Red, purple and green tuffaceous siltstone, sandstone and chert. ALPHA MARKER BED (5 m): red and white tuff, tuffaceous siltstone
DROOK FORMATION
4d Mannings Hill Member: Greenish-grey siliceous sandstone, siltstone
4c Torbay Member: Coarse red and grey laminated sandstone
4a Broad Cove River Member: Green sandstone and chert

**Figure 10.** *Geology of Torbay Bight.*

**Table 4:** Chemical analyses of siliceous volcanic and volcaniclastic rocks, eastern Avalon Peninsula

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 69.45 | 74.35 | 74.50 | 79.60 | 79.85 | 81.10 |
| $Al_2O_3$ | 14.54 | 13.33 | 12.88 | 10.54 | 10.61 | 10.14 |
| $Fe_2O_3$ | 2.77 | 0.66 | 1.94 | 1.63 | 0.25 | 0.73 |
| FeO | 0.84 | 1.76 | 0.61 | 0.99 | | |
| MgO | 0.74 | 0.25 | 0.97 | 0.37 | 0.54 | 0.26 |
| MnO | 0.06 | 0.07 | 0.09 | 0.07 | 0.08 | 0.03 |
| CaO | 0.90 | 0.68 | 0.80 | 0.40 | 0.51 | 0.57 |
| $Na_2O$ | 6.31 | 5.55 | 4.72 | 5.40 | 5.58 | 3.66 |
| $K_2O$ | 2.31 | 1.88 | 1.51 | 0.20 | 0.04 | 2.76 |
| $TiO_2$ | 0.48 | 0.52 | 0.41 | 0.23 | 0.09 | 0.31 |
| $P_2O_5$ | 0.13 | 0.07 | 0.05 | 0.04 | 0.05 | tr |
| Traces | 0.67 | | | | | |
| L.O.I. | 1.32 | 1.53 | 0.81 | 0.87 | 0.50 | |
| Total | 99.87 | 99.99 | 100.01 | 99.29 | 99.46 | 100.06 |

L.O.I. : Loss on Ignition
Traces (No. 2): $CO_2$:0.03%; $H_2O$:0.72%; BaO:0.09%; $ZrO_2$: 0.03%.

1. Red tuff, adjacent Dogberry Hill Gabbro, Dogberry Hill Road – Millers Road. Sample: AK85-168D (47°34'00"N, 52°52'50"W). Analysis: Mineral Development Division
2. 'Soda rhyolite'. Grey recrystallized welded tuff, ignimbrite sheet, Colliers Peninsula (Papezik, 1969, Table 1, Sample: C-GR).
3. Red vitric tuff, Middle Cove Member, Pitts Memorial Drive, 1.6 km east of TCH. Sample: AK 84-118 (47°30'40"N, 52°50'00"W). Analysis: Mineral Development Division.
4. Vitric chert, Middle Cove Member, Middle Cove (Hughes, 1976, Table 2, No. 5)
5. Red vitric tuff, Middle Cove Member, south of Runway 11/Alpha, St. John's Airport. Sample: AK85-125 (47°37'20"N, 52°46'10"W). Analysis: Mineral Development Division
6. Vitreous chert, Octagon Pond Member, Octagon Pond (Hughes, 1976, Table 2, No. 7)

Member) along the margins of the Princes Lookout Formation.

*Structural Relations and Correlation.* The Octagon Pond Member is not in exposed contact with any other rock units and its stratigraphic position within the Drook Formation is therefore uncertain. The lowest exposed beds in the quarry are assumed to be in fault contact with the Hibbs Cove Member (Mistaken Point Formation), east of Brazil Pond.

South of Mitchells Pond (near survey monument # 026628 on the Paradise Road map sheet), thin beds of streaky-laminated, coarse-grained sandstones similar to those of the Torbay Member, are intercalated with the cherts; the Octagon Pond Member is therefore assumed to underlie the Torbay Member. Along the southwestern border of the map area between Adams, Topsail and Octagon ponds, the Octagon Pond and Broad Cove River members are juxtaposed along the unexposed axis of the Paradise Syncline; assuming no major fault separates them, then they are presumed to be correlatives.

### *Bauline Line Member (Subunit 4b)*

*Name, Distribution and Thickness.* The name Bauline Line Member, is proposed for a distinctive volcanogenic mixtite, which has interbeds of silty sandstone, sporadically exposed along the Bauline Line between Portugal Cove and Bauline Road. Northeast Pond River is designated as the type section of this specially developed part of the Drook Formation. For about 300 m downstream of Northeast Pond, good exposures of between 1- to 10-m-thick units of mixtite are separated by thinner stratified units of streaky-laminated sandstone (Torbay Member); the member is underlain by green silty sandstone and chert (Broad Cove River Member). The estimated thickness of this assemblage from the base of the lowest mixtite unit to the top is 200 m, although some structural repetition is possible (Figure 9).

The Bauline Member is also exposed in a number of localities to the west of the Flat Rock Thrust, e.g., between Gallows Cove Pond (Torbay) and Red Head (Flat Rock). An easily accessible reference section occurs along Piccos Brook, downstream from the Wind Gap Road bridge (see Figure 19; Plate 15).

*Lithology and Structural Relations.* The Bauline Line Member is a distinct and easily recognizable unit of the Conception Group. The main features of the member are:

1. mixed coarse-fine deposits (mixtite) consisting of disorganized conglomerate and coarse grained to pebbly sandstone
2. thick, tabular to wedge-shaped mixtite units intercalated with thin interbeds of siliceous volcaniclastic sandstone, siltstone and mudstone
3. planar erosive surfaces at the base of coarse mixtites
4. rapid lateral and vertical facies changes within a marine sequence
5. limited geographic extent
6. lack of features indicative of past glaciations (e.g., striated, faceted clasts, outsize clasts or dropstones within well-stratified beds).

The mixtite-facies consist of poorly sorted, randomly oriented, pebble to boulder size (up to 30 cm) clasts set in a muddy sandy matrix (Plates 16 and 17). Clast/matrix ratios are extremely variable, even in individual localities, hence the term mixtite. The most common clasts are large pebbles to small cobbles of pink to pale green rhyolite, rhyolite porphyry, ignimbrite, siliceous siltstone, sandstone, and minor (10 percent or less) basalt, mafic tuff, granite, granophyre and quartzite. Most of the larger clasts are subrounded having a combination of spherical, disc and rod shapes. Small clasts (< 32 mm) are commonly angular or show both angular and subrounded faces due to fracturing

**Plate 15.** *Thick, tabular mixtite unit intercalated with volcaniclastic sandstone. Bauline Line Member, Piccos Brook, Flat Rock.*

**Plate 16.** *Pebbly mixtite facies of Bauline Line Member. Felsic volcanic pebbles set in a muddy, sandy matrix, which were injected into fractured clasts. Type locality, Bauline Line.*

of larger clasts; tabular and equant shapes predominate. No glacially striated clasts or fragments exotic to the Avalon Peninsula were observed.

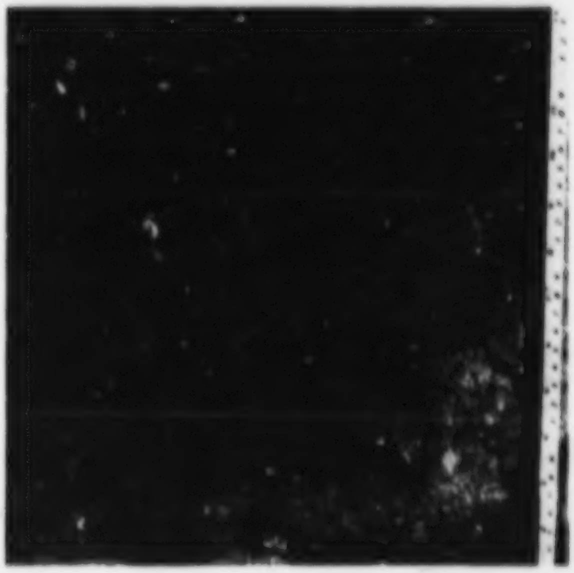


**Plate 17.** *Mixtite facies consisting of pebble- to boulder-size clasts set in a muddy sandy matrix, which constitutes about 60 percent of rock sample. Type locality, Bauline line.*

The clasts are set in a greenish grey to purple, dominantly sandy matrix. Clast/matrix ratios are extremely variable even in small exposures; matrix, for example may form 25 to 90 percent of the rock, but generally is about 60 percent. Most matrix grains show high sphericity, are generally subrounded, and are in the medium- to coarse-sand-size range. The matrix composition is similar to that of the clasts.

Individual mixtite units are parallel-sided to wedge-shaped having sharp, well demarcated tops and bottoms. There is no obvious scouring of underlying beds, although thin-bedded siltstones, overlain by disorganized cobble conglomerate, locally show low-angle truncation by a planar surface of erosion. Some mixtite tops are graded and pass upward into rhythmically bedded units of green-grey silty mudstone and silty sandstone (rhythmites). Others are locally scoured and overlain by cross-laminated sandstone. No dropstones were observed, although granules and small pebbles form clast-dominated laminae intercalated with some siltstones. Some mixtite units show localized slump beds, and load and transposition structures; these syndepositional features were facilitated by liquefaction of the matrix.

The Bauline Line Member is composed of a number of mixtite units that pass both vertically and laterally into the Torbay Member by intertonguing. Arbitrary lateral boundaries are placed between the two equivalent units. The vertical stratigraphic position of the Bauline Line Member with respect to the Torbay Member is also variable. For example, it appears near the top of the Torbay Member in the Gallows Cove Pond area, within the Torbay Member near Piccos Pond, and rests on the Broad Cove River Member south of Northeast Pond. Mixtite was not observed elsewhere in the Torbay Member.

These features suggest that the coarse-grained mixtites of the Bauline Line Member are linear rather than tabular bodies, and may represent nested submarine-fan channel deposits having limited lateral continuity of individual channels, perpendicular to the flow. The lateral shifting of numerous distributary channels on a middle-fan area would result in lateral facies changes, planar erosive surfaces and thinning- and fining-upward sequences (e.g., Howell and Normark, 1982, p. 379).

*Correlation.* The 300-m-thick Gaskiers Formation (Figure 3) of the southern Avalon Peninsula is a Precambrian tillite formed by a combination of processes (Williams and King, 1979; Anderson and King, 1981). Mixtites of the Bauline Line Member and the Gaskiers Formation are dominated by mass-flow processes and as a result have many lithological similarities. Significant differences have been cited that suggest they formed independently. For example, vertical and lateral facies variations in the Bauline Line Member reflect local migration of the unit through space and time. Temporal correspondence of the two units cannot be demonstrated, only assumed. Lithocorrelation, (linking units of similar lithology and stratigraphic position) immediately above and below the mixtites in northern and southern Avalon Peninsula is not feasible, except in a very general way. The Bauline Line Member is therefore regarded as a unit within the Drook Formation and a possible penecontemporaneous northern lithofacies of the Gaskiers Formation.

### *Torbay Member (Subunit 4c)*

*Name, Distribution and Thickness.* Distinctive beds of streaky, silty sandstone, exposed in the Torbay area, correspond with the lower part of the 'Torbay Slate' of Walcott (1899), and hence the town of Torbay is selected as the name of this new member. Isolated exposures of the unit occur on the hilly slope between the Torbay Post Office and southwestern Torbay Bight (i.e., within the Torbay Dome); this area is designated the type locality (Figure 7). Thick, representative exposures of the unit are found along the banks of Island Pond Brook commencing 40 m downstream from the Torbay Road bridge and extending to Torbay Bight (Figure 10). However, because the stratotype is incomplete, it is supplemented by several reference sections.

The principal reference section is designated in the Broad Cove River—Thorburn Road area between Hogans Pond Road (starting 190 m east of survey monument # 026673, map sheet 0252) and the Dogberry Hill bridge (300 m west of survey monument # 026674, map sheet 0252). Here, the Torbay Member has an estimated stratigraphic thickness of 750 m (Figure 9) and forms part of the steeply eastward dipping limb of the Paradise Syncline. Sporadic exposures across this belt are considered representative of the unit as a whole. An abandoned quarry, 300 m southeast of South Pond (easily accessible by Quarry Road south of Torbay), provides a good vertical profile through 30 m of strata. Good exposures, representative of the upper part of the unit, occur at Big Pond where they form the core of the Pippy Park Dome; a comparable sequence was temporarily exposed in the Torbay Dome during road—pipeline construction in 1985.

*Lithology.* The Thorburn Road section provides a good vertical profile through the Torbay Member (Figure 9). This sequence, bounded by the Broad Cove River Member to the west and the Mannings Hill Member to the east, is divided into three broad lithofacies, which in ascending order are:

| | |
|---|---|
| A-4c | evenly laminated siltstone and sandstone |
| B-4c | streaky laminated sandstone |
| C-4c | unevenly laminated, red tuffaceous mudstone and quartzose sandstone. |

The lower facies (A-4c) consists of laminae of alternating pale- to dark-green siltstone, greenish-grey sandy siltstone and grey, medium to very coarse sandstone. In the field, it was referred to as pin-stripe or varve-like facies because separation of laminae of specific sizes into 0.1 to 1 cm bands gave rise to rhythmic colour variations. The boundaries between the laminae are sharp, but locally show normal and inverse grading. Shards occur in the siltstones but are usually fragmented. Volcanic detritus and quartz grains form most of the sandstones. Traces of cross-lamination are recorded in lenticular sandstone and appear to have been formed by migrating starved current ripples (i.e., by sand grains avalanching over lee-side silts).

About 75 percent of the member is characterized by a streaky-laminated-sandstone facies (B-4c). The boundary with the underlying facies is by interfingering. Distinctive streaky laminae and lenses of light-grey silty sandstone, quartzose sandstone and orthoquartzite are irregularly interspersed in a dominantly olive-green arkose (Plate 18). Medium- to coarse-grained arkosic sandstones contain over 25 percent plagioclase (twinned albite, perthite), variable amounts of corroded, angular to subrounded quartz and minor subangular grains of rhyolite, granophyre, basalt, chlorite and epidote.

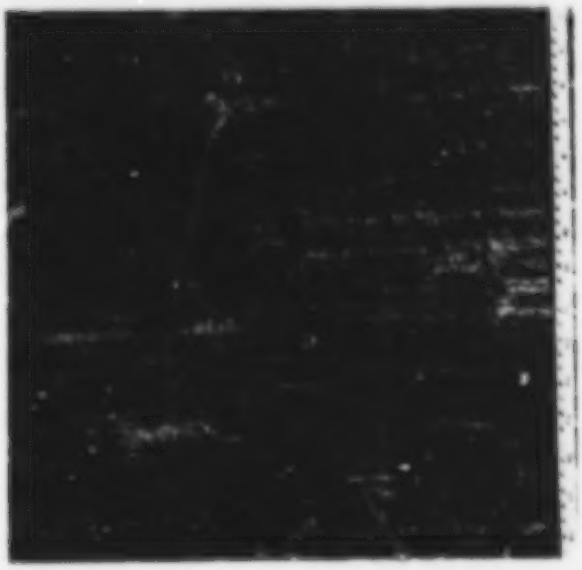


**Plate 18.** *Streaky-laminated-sandstone facies (facies B-4c), Torbay Member, Thorburn Road.*

The upper 10 to 20 m of the Torbay Member is unique with respect to the Conception Group and has not been recognized elsewhere on the Avalon Peninsula. This locally widespread facies (C-4c) is gradational into the underlying facies (B-4c) and consists of uneven lenses and laminae composed of arkose, quartzose sandstone and orthoquartzite, intercalated with thin wispy laminae of red tuffaceous mudstone. Sandstones are medium to coarse grained and typically contain 75 percent or more of rounded to subrounded quartz, 5 to 25 percent plagioclase (mainly albite and perthite), and the remainder mainly rock fragments (e.g., rhyolite, granophyre). This rock unit has relatively high porosity and permeability.

*Structural Relations.* Structurally, the Torbay Member is a very competent unit and forms large-scale structural domes (e.g., Torbay and Pippy Park domes). As the most competent unit also in intervening basins (e.g., Windsor Lake Basin) it determines the structural style. In the Torbay to Flat Rock area, it forms the leading edge (upper) of the Flat Rock Thrust (Figure 10).

The Torbay Member conformably overlies the Broad Cove River Member in the western part of the map area, but its base is unexposed in the large structural domes to the east. It is laterally interfingered with mixtites of the Bauline Line Member. The streaky-laminated-sandstone facies (B-4c) of the Torbay Member is overlain and locally intercalated with thick-bedded siliceous sandstone and chert of the Mannings Hill Member; examples of interfingering can be seen in the type locality west of Torbay Bight (Plate 19). Minor beds of the streaky-laminated facies locally occur in the Middle Cove Member (Mistaken Point Formation), mainly in the vicinity of Middle Cove (Figure 11).

*Correlation.* North of the map area, both the Torbay and Bauline Line members may be traced in a narrow (0.5 to 1 km wide), linear belt from the Bauline Line–Bauline Road junction to steep coastal cliffs between Shoe Cove Brook and Shoe Cove Island. Keats (1968) estimated an exposed stratigraphic thickness of about 2500 ft (760 m) for 'laminated arkosic sandstones' (equivalent to the Torbay Member) exposed in near vertical cliffs around Shoe Cove. Green-grey laminated to massive arkosic sandstone having intercalated green argillite is well exposed between Shoe Cove and the western part of Pouch Cove (Hsu, 1975, map unit 4); this unit is a correlative of the Torbay Member. The Torbay Member does not have an exact equivalent in the southern Avalon Peninsula and is best regarded as a coarse facies within the upper part of the Drook Formation.

A green siltstone, laminated sandstone and tuff assemblage (subunit 4cx) is associated with major thrusts along the margins of the Princes Lookout Formation. Although its stratigraphic position is uncertain, it is presumed to be a highly tectonized facies of the Torbay Member.

### *Mannings Hill Member (Subunit 4d)*

*Name, Distribution and Thickness.* The name Mannings Hill Member is here formally proposed for green siliceous silty sandstone and bedded cryptocrystalline chert of volcanic origin exposed in the Mannings Hill–Torbay Road intersection, opposite the Torbay Post Office (Plate 20). The stratigraphic thickness of the unit, sporadically exposed along the Torbay Road between Island Pond Brook and Watts Pond, is estimated to be about 500 m. It forms a poorly exposed belt around the Torbay Dome and likewise, around the southwestern margin of the Windsor Lake Basin (Figure 7); its estimated stratigraphic thickness here is 250 m. Along the axis of the Paddy's Pond Anticline, roadcuts and quarries between Bremigens and Paddy's ponds indicate that the unit is about 500 m thick; this section is designated as a reference section (road construction along the Trans-Canada Highway during 1983-85, provided a virtually complete cross-section, which was subsequently infilled).

*Lithology.* White to yellowish-green-weathering, intercalated thick siliceous sandstone, siltstone, chert and graded tuffaceous sandstone are characteristic of the type sections of both the Mannings Hill Member and the Drook Formation at Drook.

**Plate 19.** *Streaky-laminated-sandstone facies of Torbay Member (lower centre) overlain by dark siliceous sandstone and chert of Mannings Hill Member, Torbay.*

Roadcuts and quarries in the Mannings Hill Member between Bremigens and Paddy's ponds along the axis of the Paddy's Pond Anticline, consist dominantly of parallel-sided, medium- to thick-bedded, dark-green siliceous silty sandstone alternating with thin bedded, yellowish-green tuffaceous siltstone, green chert and minor mudstone. Locally, the siliceous rocks contain abundant pyrite cubes and show black dendritic growths of pyrolusite along fractures; both limonite and manganese stains are common on fracture surfaces indicating highly oxidizing conditions.

Common sedimentary structures in this turbiditic sequence include graded bedding, convolute lamination, parallel and small-scale ripple cross-laminations, rip-up clasts, and sole and load marks (Figure 12). The presence of tuffs and cryptocrystalline chert of volcanogenic origin indicates active volcanism during sedimentation.

*Structural Relations.* The Mannings Hill Member conformably overlies the Torbay Member in the Paddy's Pond Anticline and in the Windsor Lake Basin. In the type section, sandstones and cherts of the unit sharply overlie the greenish-grey streaky-laminated sandstones of the Torbay Member (Plate 19); this boundary is exposed between the Torbay Road bridge and St. Nicholas Hall. In the Torbay Dome it is locally intercalated with the Torbay Member.

Throughout most of the map area, the Mannings Hill Member passes vertically upwards by interfingering with the medium-bedded siliceous sandstones and variegated tuffs, typical of the Middle Cove Member (Mistaken Point Formation). This gradational zone, up to 50 m thick, is poorly exposed. The boundary is necessarily arbitrary and is drawn at the lowest readily traceable variegated chert–tuff sequence. In the southern Avalon Peninsula, the Drook and Mistaken Point formations are separated by the Briscal Formation and their definition is clear; in the northern Avalon Peninsula there is no apparent disconformity between the Drook and Mistaken Point formations.

*Correlation.* The Mannings Hill Member has the characteristic white to yellow and green-weathering thick beds of siliceous sandstone that make the Drook Formation so distinctive, throughout the Avalon Peninsula. The unit has been traced north of Watts Pond, along the Pouch Cove Highway and thence to Stiles Cove. Superb examples of the Mannings Hill Member are exposed in steep coastal cliffs between Stiles and Red Head coves; this section is designated as the reference section and is mainly accessible by boat. On the north side of Small Point, the unit is overlain by medium bedded sandstones of the Mistaken Point Formation.

## Mistaken Point Formation (Unit 5)

### *Name, Distribution and Thickness*

The name 'Mistaken Point Formation' was proposed by Williams and King (1979) for the interbedded greenish-grey

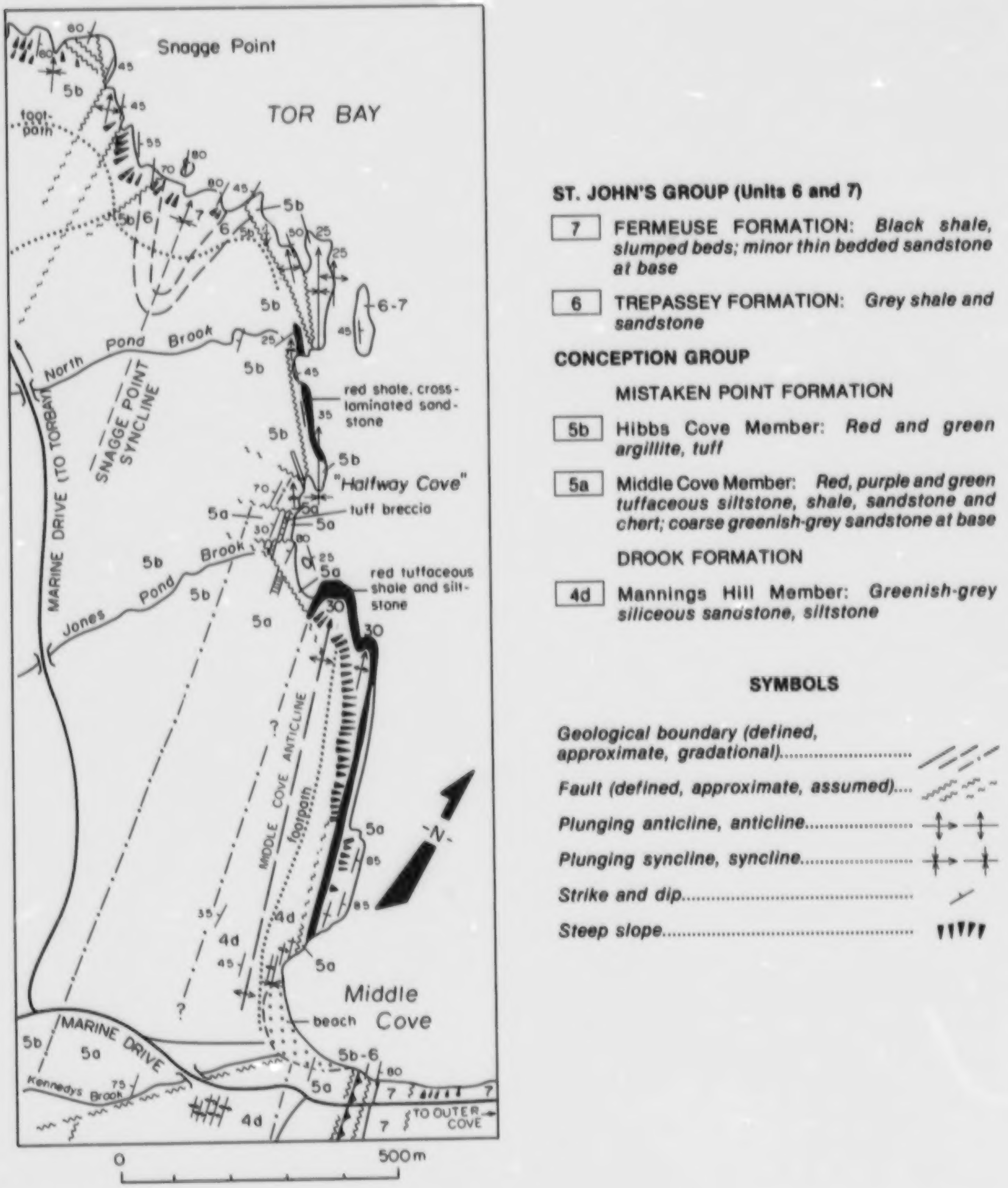

Snagge Point
TOR BAY
foot-path
5b
6
7
6-7
North Pond Brook
SNAGGE POINT SYNCLINE
MARINE DRIVE (TO TORBAY)
red shale, cross-laminated sandstone
"Halfway Cove"
tuff breccia
5a
Jones Pond Brook
red tuffaceous shale and siltstone
MIDDLE COVE ANTICLINE
footpath
4d
N
Middle Cove
beach
MARINE DRIVE
Kennedys Brook
5b-6
TO OUTER COVE
0
500 m
ST. JOHN'S GROUP (Units 6 and 7)
7 FERMEUSE FORMATION: Black shale, slumped beds; minor thin bedded sandstone at base
6 TREPASSEY FORMATION: Grey shale and sandstone
CONCEPTION GROUP
MISTAKEN POINT FORMATION
5b Hibbs Cove Member: Red and green argillite, tuff
5a Middle Cove Member: Red, purple and green tuffaceous siltstone, shale, sandstone and chert; coarse greenish-grey sandstone at base
DROOK FORMATION
4d Mannings Hill Member: Greenish-grey siliceous sandstone, siltstone
SYMBOLS
Geological boundary (defined, approximate, gradational)
Fault (defined, approximate, assumed)
Plunging anticline, anticline
Plunging syncline, syncline
Strike and dip
Steep slope

**Figure 11.** *Geology of the Snagge Point–Middle Cove area, Tor Bay.*

**Plate 20.** *Siliceous sandstone and chert of Mannings Hill Member in type locality, opposite Torbay Post Office.*

and reddish-purple tuffaceous siltstones, shales and sandstones that conformably overlie the Briscal Formation, in the southern Avalon Peninsula (Figure 6). At its type section on Mistaken Point (Figure 3), the formation is profusely fossiliferous having a variety of frond-like and disc-like impressions (Anderson and Misra, 1968; Misra, 1969a, b, 1971; Williams and King, 1979; King, 1982; Anderson and Conway Morris, 1982; King *et al.*, 1988). The late Precambrian fossils occur on bedding plane surfaces and in most cases occur beneath dark, thin tuff horizons that are less than one centimetre thick. Fossil horizons are most common toward the top of the formation; five or more fossiliferous horizons are easily identified at the type locality (King *et al.*, 1988).

The fossiliferous Mistaken Point strata define both a biostratigraphic zone and a lithostratigraphic unit. The concentration of thin tuff beds near the top of the formation indicates that it is an actual chronologic unit as well. Tuff in the lower part of the type section of the Mistaken Point Formation has yielded a radiometric U–Pb date of 565 ± 3 Ma (Benus, 1988). This easily recognized formation was chosen by Williams and King (1979) to define the top of the Conception Group. It has been traced northward from the type locality to Cape Broyle, where it directly overlies the Drook Formation (Figure 6), and from there, through St. John's area to Torbay (Figure 3). The formation is about 400 m thick throughout the Avalon Peninsula.

The Mistaken Point Formation corresponds to the upper part of the 'Torbay Slate' of Walcott (1899). It is composed of relatively less competent rocks than the underlying Drook Formation and forms a structural zone characterized by open to tight folds. The stratigraphic thickness of the formation ranges between 300 and 500 m, with an average thickness of 400 m (Figure 9). The Mistaken Point Formation is here subdivided into two new members.

### *Middle Cove Member (Subunit 5a)*

*Name, Distribution and Thickness.* The name Middle Cove Member is here formally proposed for the medium bedded, graded, fossiliferous sandstone and variegated tuffs and cherts that are present in the lower part of the Mistaken Point Formation. These rocks are well exposed in a 1-km-long coastal belt to the north of Middle Cove. This locality (Figure 11) provides the most complete profile of the unit and is designated as the type section. Minor east–west trending strike-slip faults are present but marker beds of tuff facilitate correlation and continuity of sequence. The estimated thickness of the unit in the type section is about 100 m, which is maintained throughout the area.

*Lithology.* The type section provides both a vertical and lateral profile of the Middle Cove Member. A very thick red tuffaceous mudstone–siltstone unit, prominently exposed in vertical to steeply eastward dipping beds at the north end of Middle Cove Beach (east of a sewer outfall), is taken as the base. It can be traced 600 m to the north-northeast, and then around the nose of the Middle Cove Anticline.

At 'Halfway Cove', the succession is exposed on a wide (50 to 100 m) wave-cut platform across the west dipping limb of the north-plunging anticline. Coarse sandstones of the Mannings Hill Member, exposed in the core of the Middle Cove Anticline are directly overlain by red tuffaceous mudstone and siltstone, followed by a generally fining upward sequence of graded siliceous turbiditic sandstone and interbedded siliceous siltstone, chert and tuff. As the average bed thickness decreases upward from medium to thin, the ratio of tuff and silt over sand increases upward. The top 10 to 20 m of this approximately 100-m-thick unit is capped by pale-green silicified tuff and pyritiferous tuffaceous siltstone; this facies is present throughout the area and defines the top of the member.

Most of the beds in the type section are tuffaceous and very siliceous. Varieties include lithic, vitric and lapilli tuffs. Red mudstone and lithic tuff (up to 2 m thick) are interbedded with very fine grained turbidites throughout the unit, but are thickest and best developed in the upper part of the succession. Variable amounts of lithic fragments occur in most beds and are mainly rhyolite, rhyolite porphyry, ignimbrite and granophyre (Figure 13). Medium bedded units are commonly colour-banded and have sharp bases; devitrified glass shards are recognizable in graded tops. Dark, hematitic colour bands within individual beds frequently highlight convolute and ripple–drift laminae. Some beds show load casts and planar cross-bedding. Rare, disc-like markings on the tops of some turbidites resemble medusoid impressions and are comparable with those of Mistaken Point; they are covered by a veneer of brown volcanic ash.

Distinctive marker or key beds, of red waterlain tuffaceous siltstone and white to reddish purple lithic tuff,

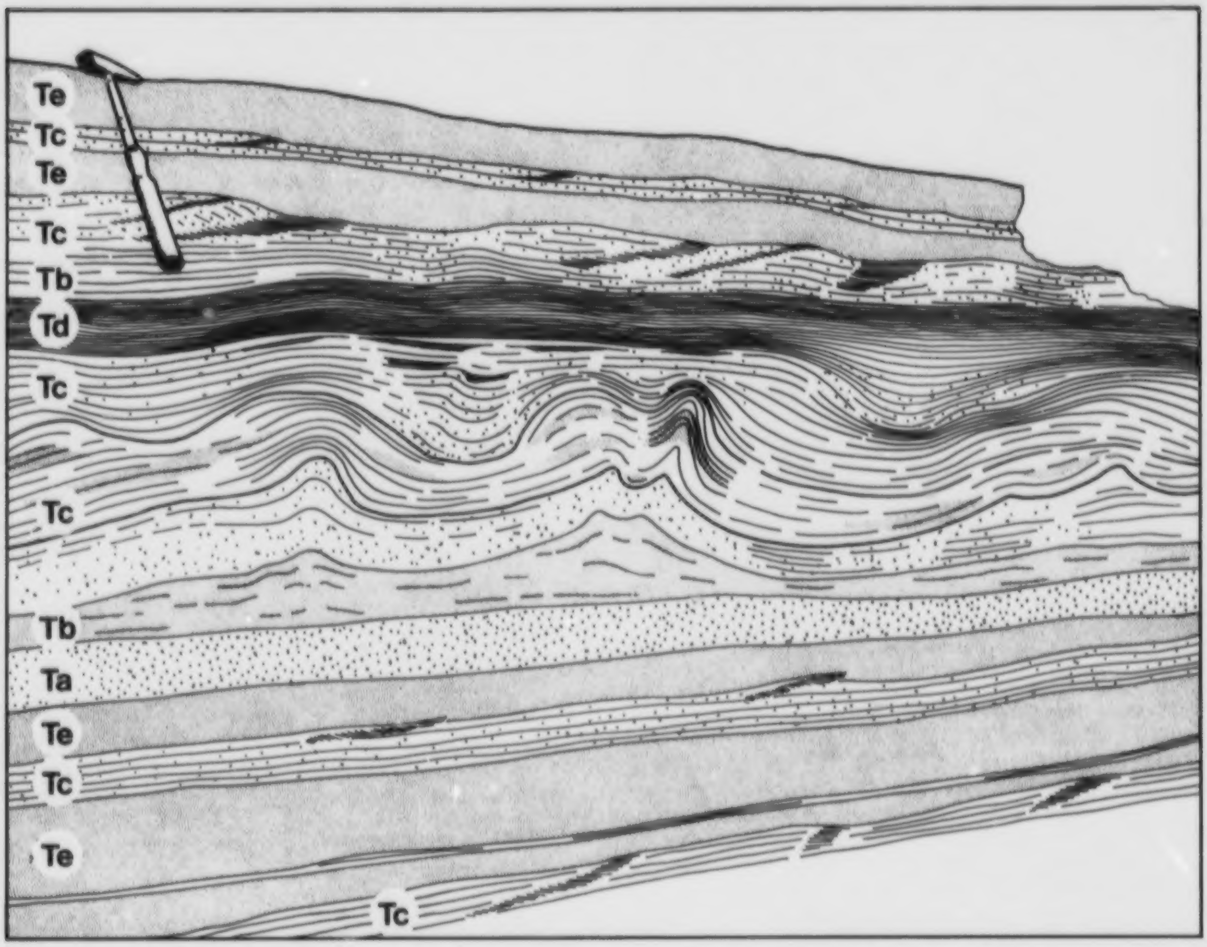


**Figure 12.** *Turbidite and hemipelagic subdivision in the upper part of Mannings Hill Member, Paddys Pond Anticline.*

occur near the top of the Middle Cove Member throughout the area (Figure 7) and form both a chronostratigraphic and a lithostratigraphic unit (Unit 5 m). Excellent examples of this unit are exposed near runway Alpha, St. John's Airport, and about 600 m south-southwest of Snagge Point (Figure 10), on the south side of Torbay Bight. At the latter locality, 7.7 m of red to purple siliceous siltstone (Plate 21) is overlain by 12.5 m of white-weathering siliceous lithic tuff. The former is parallel-laminated with minor intercalations of cross-laminated silty tuffaceous sandstone, lithic tuff and vitric tuff. In contrast, the siliceous tuff has a very glassy or rhyolitic appearance, is internally massive to poorly bedded and is crowded with a variety of large (0.5 to 10 cm) lithic fragments. Tabular to ellipsoidal rhyolite, with minor granophyre, chert and mafic clasts occur in a fine chaotic matrix of quartz and feldspar (albite). Shards are present, but broken slivers are difficult to distinguish from small chips of volcanic quartz.

*Chemistry.* Chemical analysis of these tuffs indicates that they have a composition close to alkali rhyolite (Table 4, Analysis 2). Hughes (1976) suggested that the high silica content, relative to that of $Al_2O_3$ in some Conception Group siliceous rocks, may have to do with secondary processes such as release of silica during devitrification, and active migration and concentration in diagenesis. Hughes (1976) also noted that the predominant plagioclase is albite, and presumed it was pseudomorphing an original more calcic plagioclase.

*Structural Relations and Correlation.* The Middle Cove Member conformably overlies and is interfingered with the Mannings Hill Member (Drook Formation). It is in sharp, conformable contact with the overlying argillaceous rocks of the Hibbs Cove Member. Siliceous, well-bedded tuffs of the Middle Cove Member, exposed on the steeply eastward dipping limb of the Middle Cove Anticline at the eastern end of Middle Cove beach, are in presumed fault contact with grey shales of the St. John's Group as virtually all of the Hibbs Cove Member is missing (Figure 11).

Volcanogenic silicified rocks of the Middle Cove Member are readily traceable around the perimeters of structural domes and basins in the area. The boundary with

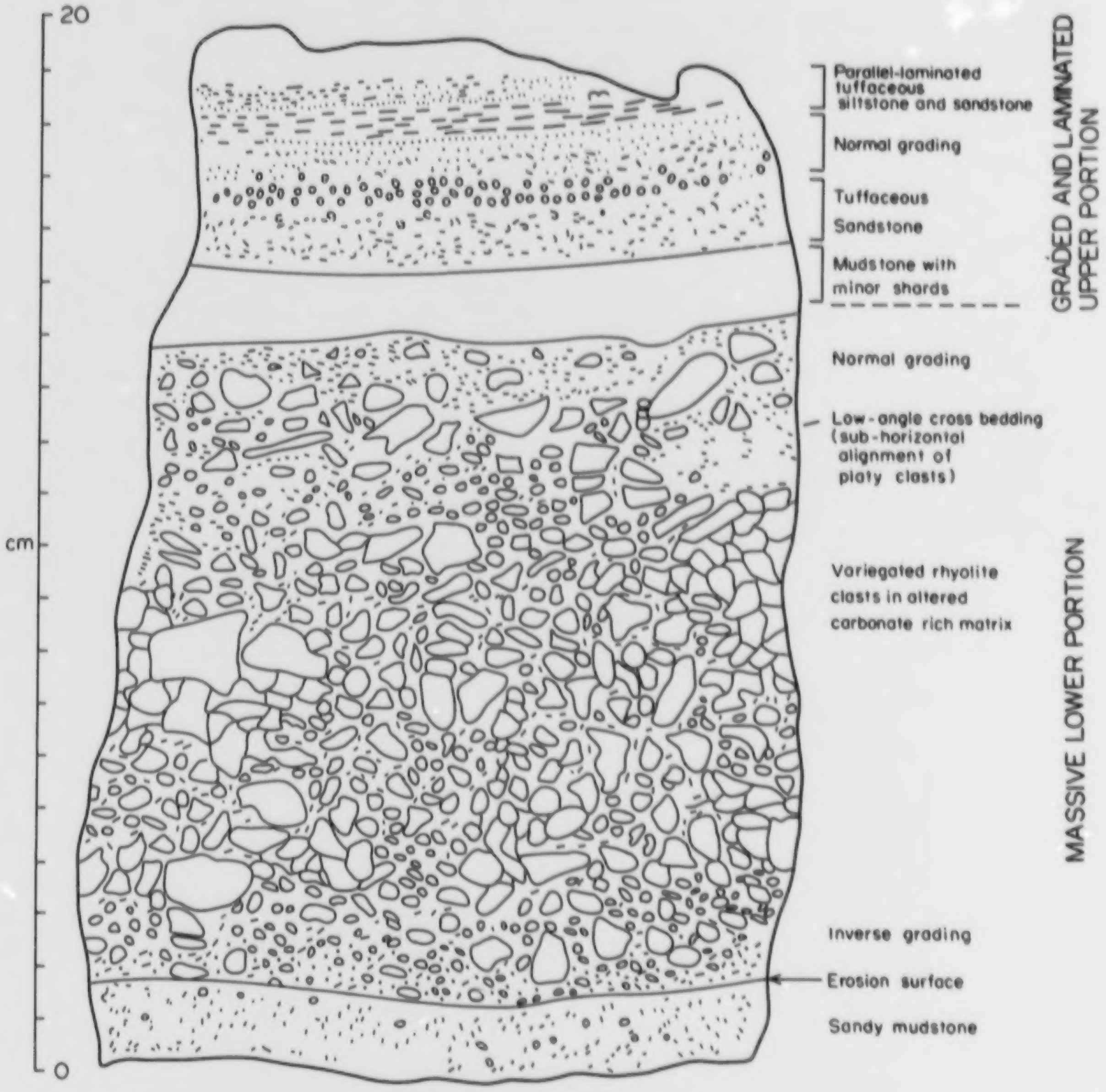

20
cm
0
Parallel-laminated tuffaceous siltstone and sandstone
Normal grading
Tuffaceous Sandstone
Mudstone with minor shards
GRADED AND LAMINATED UPPER PORTION
Normal grading
Low-angle cross bedding (sub-horizontal alignment of platy clasts)
Variegated rhyolite clasts in altered carbonate rich matrix
MASSIVE LOWER PORTION
Inverse grading
Erosion surface
Sandy mudstone

**Figure 13.** *Subaqueous pyroclastic flow unit. Inverse grading in massive lower portion reverts upward to normal grading; alternating fine- to coarse-grained ash beds form the upper portion. Middle Cove Member, Stick Pond.*

the overlying softer argillaceous rocks of the Hibbs Cove Member is typically marked by an abrupt change in relief, in part structurally controlled, but largely emphasized by differential erosion; thick (5 m or more) accumulations of till occur along this boundary and may obscure the erosional surface.

*Hibbs Cove Member (Subunit 5b)*

*Name, Distribution, Thickness and Correlation.* The Hibbs Hole Formation, first named by Hutchinson (1953), is found at the top of the Conception Group. As the formal name Hibbs Hole Formation has been abandoned, and the type locality of Hibbs Hole has been renamed Hibbs Cove, it is therefore proposed that the name Hibbs Cove Member (Mistaken Point Formation) replace it but the original type-locality and description (Hutchinson, 1953) be retained. The reddish purple and green colour and dominance of fine-grained clastic sedimentary rocks having a slaty cleavage is characteristic of this unit. In the type locality at Hibbs Cove, it is 135 m thick (Hutchinson, 1953). Subsequent field studies showed that it is too small a unit for reproduction on regional

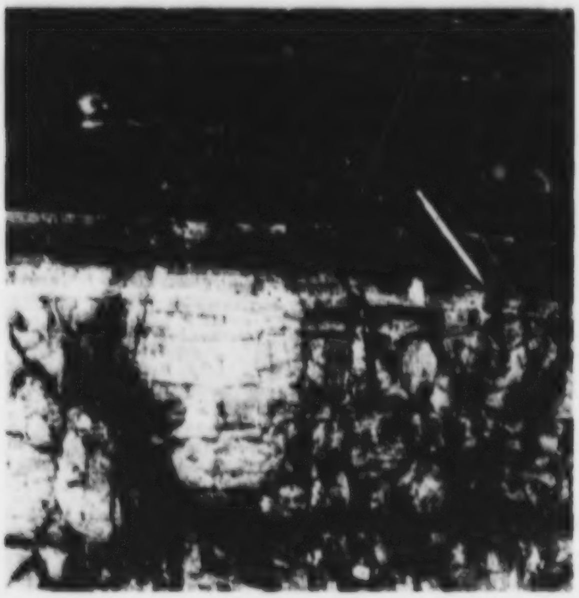


**Plate 21.** *Parallel- and convolute-laminated siliceous siltstone, tuff and mudstone of the Middle Cove Member, south side of Torbay Bight.*

geological maps (e.g., McCartney, 1967); in the southern Avalon Peninsula, the Hibbs Cove Member forms a minor unit above the metazoan fossils but is impractical to map. Despite its thinness in some areas, it can be traced throughout much of the central and eastern Avalon Peninsula; between Mistaken Point and Torbay, it gradually increases in thickness from about 10 to 20 m in the south, to about 300 m in the Donovans area.

The Hibbs Cove Member in the map area maintains an estimated average thickness range of 200 to 300 m; the presence of numerous small folds and faults within all sections leaves this estimate open to error. Easily recognized red and green argillaceous beds of the Hibbs Cove Member are highly susceptible to frost action (Plate 11), and are therefore only exposed in the low ground between intervening structural domes where they display an intricate pattern of interference folds.

*Lithology.* The Hibbs Cove Member consists of mainly distinctive green and reddish purple argillaceous siltstones and very fine grained sandstones. Exposures at Snagge Point (Figure 11) show that green to red colour changes are diagenetic and may be independent of bedding. Numerous roadcuts and quarries along the Paddy's Pond Anticline provide the least deformed profile of the member. Although the argillaceous rocks of this unit commonly have a massive appearance, medium to thick beds, parallel laminations and grading are recognizable. They can be distinguished from similar looking argillaceous rocks in the Drook Formation by their softness, cleavage and tabular to irregular fracture; these fractures are the primary conduits for groundwater movement as they show iron and manganese staining and make the rock highly susceptible to frost action. Drill-hole samples, from the argillaceous units within the Hibbs Cove Member, are frequently ground to a clay in contrast with the hard siliceous rock chips from the Drook Formation.

*Contact Relations and Correlation.* The Hibbs Cove Member sharply overlies the Middle Cove Member with conformable contact (Figure 9). This boundary also represents a divide between highly silicified rocks below and weakly to non-silicified rocks above, which in turn reflects a rapid decline in both acidic volcanism and Conception Group facies. Only minor tuff laminae are present in the Hibbs Cove Member in contrast to abundant tuff in the Middle Cove Member.

Argillaceous rocks of the Hibbs Cove Member are apparently conformably overlain by the grey sandstones and shales of the Trepassey Formation in the northeastern part of the Donovans Industrial Park. Although the boundary between them is unexposed, it is assumed to extend from the Donovans Industrial Park (close to Fourth Street, Mount Pearl) southward, in close proximity to the Ruby Line—Pitts Memorial Drive overpass.

## ST. JOHN'S GROUP (UNITS 6 to 8)

### Definition

The Conception Group is conformably overlain by up to 2 km of marine shales and interbedded sandstones of the St. John's Group (Williams and King, 1979), interpreted by King (1980) as a pro-deltaic to shallow-marine sequence that progrades and thickens southward (Figure 6).

The group consists of three units of formational status, which in ascending order are the Trepassey, Fermeuse, and Renews Head formations (Williams and King, 1979). The Fermeuse and Renews Head formations were previously mapped as St. John's Slates (Jukes, 1842, 1843), Aspidella Slates (Murray and Howley, 1881a, b), Momable Slate (Walcott, 1899), and St. John's Formation (Rose, 1952). King (1980) showed that the Carbonear Formation (Hutchinson, 1953) on the western side of Conception Bay is divisible into three units, which can be correlated with those in the St. John's Group of Williams and King (1979). The name Carbonear Formation was replaced by St. John's Group (King, 1988); rocks of the present Carbonear Formation were first mapped and included within the St. John's Slate by Jukes (1843). Throughout the Avalon Peninsula, the Trepassey, Fermeuse and Renews Head formations constitute a continuous, conformable sequence of grey to black cleaved shales and grey to buff sandstones with gradational contacts (Figure 3).

### Local Distribution

The rock subdivisions of the St. John's Group, designated in the Trepassey area by Williams and King (1979), are all recognizable at the type locality of the St. John's Group. They form a poorly exposed, coarsening-upward sequence, stratigraphically above and to the east of

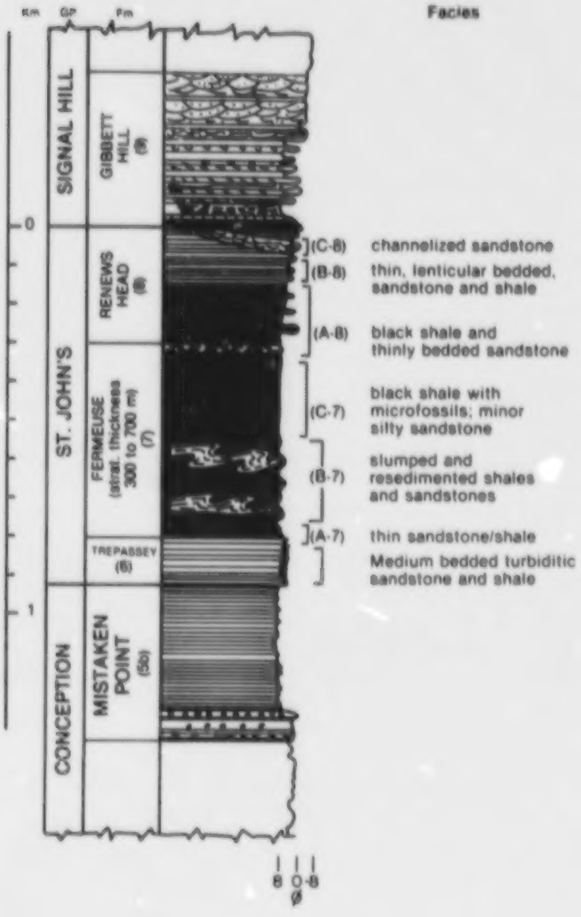

Km
GP
Fm
Facies
SIGNAL HILL
GIBBETT HILL (9)
0
ST. JOHN'S
RENEWS HEAD (8)
FERMEUSE (strat. thickness 300 to 700 m) (7)
TREPASSEY (6)
1
CONCEPTION
MISTAKEN POINT (5b)
(C-8) channelized sandstone
(B-8) thin, lenticular bedded, sandstone and shale
(A-8) black shale and thinly bedded sandstone
(C-7) black shale with microfossils; minor silty sandstone
(B-7) slumped and resedimented shales and sandstones
(A-7) thin sandstone/shale
Medium bedded turbiditic sandstone and shale
8
0
ø
-8

**Figure 14.** *Composite stratigraphic section of the St. John's Group.*

the Conception Group. The top of the St. John's Group is marked by a gradational contact with the Gibbett Hill Formation at the base of the Signal Hill Group. A composite stratigraphic section of the St. John's Group exposed in the map area is shown in Figure 14.

## Trepassey Formation (Unit 6)

### *Name, Distribution and Thickness*

The type locality of the Trepassey Formation (Williams and King, 1979) is Powles Peninsula, southeast Trepassey Harbour, southern Avalon Peninsula. Rocks of the Trepassey Formation were previously assigned to either the St. John's Formation (Rose, 1952; Hsu, 1972) or the Conception Group (Misra, 1969a, b, 1971). In the type locality, the formation is about 250 m thick and consists of medium to thickly bedded, graded grey sandstone, fining-upwards tuffaceous siltstone and shale. It has been traced northward to Torbay (Figure 3).

The Trepassey Formation is about 100 to 125 m thick. Although poorly exposed, it has been traced as a narrow sinuous belt from Torbay Bight to the Goulds. A superb coastal exposure of the formation is present on the north side of Torbay Bight (Figure 10), 500 m northeast of a prominent gulch (Tappers Cove); its exposed stratigraphic thickness there is about 100 m. Good exposures occur in Virginia River (near the Janeway Hospital) and in Rennie's River (southeast of Confederation Building). During site excavation and tunnel construction, for Memorial University of Newfoundland's M.O. Morgan Music Building, about 100 m was exposed. Between the University and Mundy Pond, its position is defined by two separate drill cores. Small sporadic exposures of the Trepassey Formation occur in Cowan Heights and along the Waterford River in the northern part of Donovans Industrial Park. Small outcrops of the Trepassey Formation occur along the western end of the Ruby Line, on the Pitts Memorial Drive near the Goulds – Mount Pearl overpass, and to the west of Goulds.

### *Lithology*

The Trepassey Formation in the map area is characterized by very fine grained green-grey sandstone, tuffaceous siltstone and grey-black shale. Medium beds form most of this 100-m-thick formation, but near the top, thin beds gradually become dominant (Figure 14). The beds are tabular and laterally persistent. Repetitive graded bedding is diagnostic; each very fine grained sandstone bed is usually graded, overlain sharply by another sandstone bed and the cycle repeated. Medium to thin interbedded sandstones, siltstones and shales in the upper part of the formation have a variety of internal-bedding features including convolute laminations, climbing ripples and small slumps. Starved lenticular ripples occur in very thinly bedded units, mainly at the top of the formation and are overlain by black shale.

The Trepassey Formation in the map area represents a transitional environment between that of the Conception and St. John's groups. It can be differentiated from the Hibbs Cove Member (Mistaken Point Formation) using the following characteristics. It has:

1. more conspicuous bedding (medium to thin beds predominate)
2. convolute laminations, climbing ripples, parallel laminations, grading, starved lenticular current ripples
3. higher sandstone to shale ratio (sandstone increases upward within the formation), and
4. lack of purple and green argillaceous units.

The sandstone beds resemble the classical turbidites of Bouma (1962), although complete Bouma sequences are uncommon; lower-plane parallel-laminae (Tb interval) and upper parallel-laminae (Td interval) may be absent, very thin or tend to merge with the convoluted or rippled interval (Tc).

### *Structural Relations*

The Trepassey Formation is gradational and conformable with the underlying red, purple and green argillaceous sandstones of the Hibbs Cove Member. The boundary is necessarily arbitrary and is selected where the medium beds of the Trepassey pass into the thick variegated beds of the Hibbs Cove Member.

The Trepassey Formation is gradational and conformable with the overlying grey-black shales of the Fermeuse Formation. On the north side of Torbay Bight, at Middle Cove and along the Waterford River (in the Donovans area) there is a 3 to 5 m zone of interfingering at this contact.

The Trepassey Formation is difficult to trace between Middle Cove and Virginia River because of poor exposure and structural complications. Only a local veneer of the Hibbs Cove Member is exposed on the east limb of the Middle Cove Anticline; there the Middle Cove Member and Trepassey Formation are structurally thinned by faults (Figure 11). Numerous northerly trending bedding faults between Outer and Middle coves extend toward Quidi Vidi Lake and are termed the Outer Cove Fault Zone. To the south of Kenmount Hill, the Trepassey Formation terminates along Donovans Fault. In water and sewer line excavations for the Cowan Heights West residential development, tightly folded rocks of the Trepassey and Fermeuse formations were observed in both conformable and highly sheared contacts.

### *Correlation*

The Trepassey Formation extends from Trepassey to Torbay and also forms a western belt extending from St. Mary's Bay to Broad Cove, Carbonear (King, 1980). In the Harbour Grace–Carbonear area, it is equivalent to the unnamed unit between Hutchinson's (1953) Hibbs Hole and Carbonear formations. The Trepassey Formation thins towards the north and is presumed to pinch out north of the Avalon Peninsula.

## Fermeuse Formation (Unit 7)

### *Name, Distribution, and Thickness*

The type locality of the shale-dominated Fermeuse Formation is the southeast corner of Fermeuse Harbour, on the southern Avalon Peninsula (Williams and King, 1979). Rocks of the Fermeuse Formation formed the major rock component of the 'St. John's Slate' (Jukes, 1843), 'Aspidella Slates' (Murray and Howley, 1881a, b), 'Momable Slate' (Walcott, 1899), 'St. John's Formation' (Rose, 1952), and the 'Middle Cove Formation' (Hsu, 1975).

The formation is about 1400 m thick in the southern Avalon Peninsula and thins northward towards St. John's (Figure 6). In the type locality of the St. John's Group, the Fermeuse Formation is incompletely exposed in the Rennie's and Virginia rivers. It is between 300 and 700 m thick, but these estimates may include tectonic repetition and omission of some units.

### *Lithology*

The Fermeuse Formation consists of three main lithofacies (Figure 14), which in ascending order are:

| | |
|---|---|
| A-7 | thin interbedded sandstone and shale |
| B-7 | remobilized facies (slumped and resedimented beds) |
| C-7 | black shales with rare or widely spaced thinly laminated sandstone–siltstone. |

The lower facies (A-7) is about 5 to 25 m thick and is transitional into the Trepassey Formation and the remobilized facies (B-7). It consists of very thin to thinly bedded, white and rusty brown sandstones, alternating rhythmically with thin to thick units of grey tuffaceous siltstone and black shale, giving the facies a ribbon-banded appearance. Cross-lamination, starved current ripples and grading are common structures. Good examples of this facies occur north of Torbay Bight, Snagge Point, Middle Cove, and Waterford River (north of Michener Avenue, Mount Pearl).

The middle facies (B-7) comprises most of the lower half or more of the Fermeuse Formation (Plate 22). Dark grey to black shales commonly display large slump folds of shale and sandstone (e.g., below the vantage point on the eastern shore of Middle Cove). These 1- to 10-m stratigraphically thick, disrupted units are conformably overlain by black shale, suggesting that the slump folds were formed by gravitational slumping of sediment on a sloping paleosurface during normal pelagic sedimentation. Localized zones show ruptured slump blocks of finely laminated shale and thin bedded sandstone. The sedimentary folding and thickening accounts for some of the thickness variations of the Fermeuse Formation. Numerous faults and tectonic folds further complicate relationships. Slaty cleavage is locally well developed.

The upper facies (C-7) of the Fermeuse Formation is also widespread throughout the Avalon Peninsula (King, 1986). This facies, comprising the upper half of the formation, consists of pyritiferous black shale with rare or occasional laminae of buff-weathering siltstone and very fine grained sandstone.

The mineralogical composition of the black shale consists of sericite, albite, quartz, and clay minerals, each forming between 20 and 25 percent of the rock, with trace amounts

**Plate 22.** *Slumped and resedimented beds of Fermeuse Formation (facies B-7), east side of Middle Cove.*

of calcite, dolomite, pyrite, magnetite and apatite (Hsu, 1972). Results of the chemical analysis of black shale samples from Ferryland are shown in Table 5.

**Table 5:** Chemical analyses of rock samples from the Fermeuse and Quidi Vidi formations

| | 1 | 2 |
|---|---|---|
| $Si0_2$ | 60.90 | 71.38 |
| $Al_20_3$ | 17.38 | 14.25 |
| $Ti0_2$ | 0.80 | |
| $Fe_20_3$ | 4.96 | 4.75 |
| Fe0 | 1.02 | 0.46 |
| Mn0 | 0.13 | |
| Mg0 | 2.29 | 0.46 |
| Ca0 | 1.56 | 3.01 |
| $Na_20$ | 2.99 | 2.28 |
| $K_20$ | 2.96 | 1.99 |
| $P_20_5$ | 0.15 | |
| $C0_2$ | 1.05 | |
| $H_20+$ | 0.16 | 1.20 |
| $H_20-$ | 3.30 | .21 |
| S | 0.12 | |
| C | 0.16 | |
| TOTAL | 99.93 | 99.99 |

1. Black shale, Fermeuse Formation, south shore of Calvert Bay, Ferryland. (Hsu, 1972, Table 5). Analysis: Geochemistry laboratory, Geological Survey of Canada, Ottawa.
2. Reddish-brown arkosic sandstone, Quidi Vidi Formation, near Signal Hill (Buddington, 1919, Table 4, p. 471).

The shales contain Vendian microfossils, including *Bavlinella* (Hofmann *et al.*, 1979). With some exceptions, most microbiota recovered are either poorly preserved, or include compressions of simple, allogenic, spheroidal and filamentous forms with long stratigraphic range. Problematical circular to oval markings from 1 to 5 cm diameter occur at top of the formation (Plate 23). They were interpreted by early workers as the trace fossil *Aspidella terranovica*, Billings, 1872. A detailed account and discussion of these markings is in Hsu (1972). Good examples of *Aspidella* were found along the Old Petty Harbour Road and cliffs near Prescott and Duckworth Streets. Commonly associated with *Aspidella* are larger disc-like varieties that resemble holdfasts; some forms may be medusoid impressions. Other unusual forms thought to represent impressions of soft-bodied fauna have been described by Anderson and Conway Morris (1982).

**Plate 23.** *Problematical markings* Aspidella terranovica *Billings, 1872, interpreted as trace fossil. Fermeuse–Renews Head boundary, Prescott Street, St. John's.*

### *Structural Relations and Correlation*

The Fermeuse Formation is gradational and conformable with the underlying Trepassey Formation. It is conformably overlain by the Renews Head Formation; the gradational zone, which is about 50 m thick, forms an arcuate belt in the eastern part of the map area and is exposed in a number of localities between Outer Cove, St. John's Harbour, and the Goulds.

The internal structure of the formation is complicated by numerous faults and both sedimentary and tectonic folds as can be seen in the only continuously exposed section on the east side of Middle Cove (Plate 22). The amount of structural repetition is indicated by the width of the shale belt, which varies from a low of 250 m (e.g. west of Logy Bay) to 5500 m in the Mount Pearl area.

Comparable facies occur in a major shale belt present in western Conception Bay area. King (1980) correlated the Fermeuse Formation with Hutchinson's (1953) lower unnamed division of the Carbonear Formation.

## Renews Head Formation (Unit 8)

### *Name, Distribution and Thickness*

The type locality of the Renews Head Formation is Renews Head, southeastern Renews Harbour, southeastern Avalon Peninsula (Williams and King, 1979). The formation is about 300 m thick in its type section, and consists of alternating laminae and very thin beds of rusty-weathering siltstone and lenticular-bedded sandstone set in dark shale. From the type section, it increases to about 700 m at Bay Bulls and then gradually thins to about 500 m in the southern part of the map area and to about 250 m at Outer Cove and Flat Rock (Figure 6).

The Renews Head Formation is restricted to the eastern part of the map area where it forms the western limb of the Blackhead Syncline (Figure 7). In the type locality of the St. John's Group, the formation is partially exposed near the north end of St. John's Harbour. Supplementary but incomplete reference sections are at Outer Cove, and between Waterford River and Shea Heights.

### *Lithology*

The Renews Head Formation differs from the Fermeuse Formation by its greater sand content and distinctive lenticular bedding. Both sand content and bed thickness increase upward. In the map area, the Renews Head Formation is divided into three main lithofacies (Figure 14):

| | |
|---|---|
| A-8 | a lower facies of mainly black shale with intercalated laminae and thin beds of rusty brown sandstone |
| B-8 | an upper facies of cosets of thin to medium sandstone interbedded with shale, and |
| C-8 | channelized sand lobes and sheets incised or present in facies A-8 and B-8. |

The lower facies (A-8) is gradational into the underlying, finely-laminated, black shales of the Fermeuse Formation. It forms most of the Renews Head Formation and in contrast with the Fermeuse Formation, consists of abundant alternating, irregular laminae, lenses and very thin beds of silty sandstone and black shale. Problematical markings *Aspidella terranovica*, Billings, 1872, occur at the base of the formation. Lenticular-bedded sandstones commonly show nested sequences of starved symmetrical and asymmetrical current ripples (Plate 24), which locally are deformed by loading and pass into pseudo-nodules (Plate 25). Good examples of this facies occur in the vicinity of Duckworth Street, lower reaches of Waterford River, Southside Road—Blackhead Road (e.g., west of Shea Heights), and along Old Petty Harbour Road.

**Plate 24.** *Lenticular-bedded sandstones and black shale of Renews Head Formation (facies A-8), Outer Cove.*

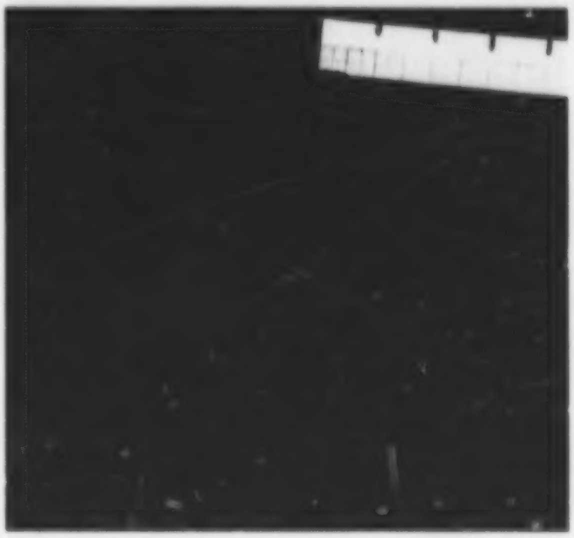


**Plate 25.** *Starved current ripples and pseudo-nodules, Renews Head Formation (Facies A-8). Grid divisions are in inches.*

Small-scale transposition and dewatering structures are present (e.g., east side of Outer Cove) and include: (1) those due to injection, such as sand dykes, sills, and plugs; (2) those due to ejection, such as sand and mud volcanoes, water-escape pipes and possible dish- and pillar-structures (Lowe and Lopiccolo, 1974; Lowe, 1976); and (3) deformational structures as small-scale disrupted beds, convolute laminations and load structures.

Facies B-8 is transitional into facies A-8 and is intercalated with the overlying Gibbett Hill Formation. It consists of predominantly medium-bedded sandstone diffusely intercalated and alternating with thin to thick units of black shale. The sandstones have sharp bases and graded tops, which frequently are reworked and show interference and straight-crested ripple marks. Internal bedding characteristics include climbing ripples and flaser bedding comparable with that in modern tidal flats (e.g., Reineck and Singh, 1973). The sandstones are fine to medium grained, moderately well sorted, and contain angular to subrounded grains of volcanic quartz (30 to 40 percent) and sodic plagioclase (25 to 45 percent) in a fine altered matrix of quartz and feldspar; rock fragments (5 to 25 percent) are predominantly rhyolite and chert associated with minor mafic volcanics. Good examples of this facies are present on the west side of Outer Cove and east of the Pitts Memorial Drive–Blackhead Road overpass.

Facies C-8 consists mainly of very thick beds of medium- to coarse-sandstone incised into facies A-8 and B-8. Three subfacies of the channelized facies C-8 are recognized, and these are defined on the basis of their geometry, size and possible origin:

C1-8: On the headland between Outer and Middle coves, 'ribbon-like sandstone bodies' interpreted as tidal-channel sands (Hsu, 1972) are embedded in thin sandstones and shales; they are long, narrow sandstone bodies, less than 20 cm wide, with U-shaped troughs up to 25 cm deep. Small scale ripple cross-laminations in the upper part of the troughs indicate flow along their long axes. These structures resemble gutter casts produced by strong locally erosive currents in shallow marine to nearshore environments.

C2-8: Associated with the U-shaped scours are broader, scour-and-fill structures. Their full dimensions or geometry could not be obtained, but in cross-section they are up to 0.5 m deep and have a channel width of at least one metre. Medium to coarse sandstone infills the channel, which sharply cuts thin bedded sandstone and shale.

C3-8: The third subfacies consists of very thick sand units interbedded with facies A-8 and B-8, and are interpreted as major channelized sand lobes and sheets. On the west side of Outer Cove, very thick (3 to 5 m), medium to coarse grained sand sheets rest sharply above rippled sandstones of facies B-8 (Plate 26); large trough crossbeds are present throughout the sand body and are overlain by asymmetrical, linguoid and interference ripples. Large (up to 10 m thick) wedge-shaped channel-fill sandstones also occur at the base of the Renews Head Formation along the Old Petty Harbour Road. Several, very thick (0.5 to 2 m), medium grained sheet sands with parallel and convolute lamination, occur in facies B-8 along the road near the entrance to the Federal Northwest Atlantic Fisheries Centre (Plate 27); possible dessication cracks occur in thin shales and sandstones below the sand sheets.

**Plate 26.** *Very thick sandstone units (facies C-8), interbedded with shales and thin sandstones (facies B-8), Renews Head Formation, Outer Cove.*

**Plate 27.** *Thick sheet-sand unit (facies C-8) interbedded with shales and thin sandstones (facies B-8), Renews Head Formation, Northwest Atlantic Fisheries Centre.*

The medium to coarse grained arkosic sandstones of facies C-8 are moderately well sorted and contain angular to rounded quartz (30 to 35 percent), sodic plagioclase (20 to 35 percent), potash feldspar (2 to 5 percent), finely divided and altered matrix of quartz and feldspar (15 to 20 percent), and rock fragments (10 to 30 percent) composed of rhyolite, chert, granophyre, with a trace of mafic volcanics. Thin, irregular laminae and lenses are locally quartz rich.

Authigenic quartz growths are present and these reduce the porosity of the rock, except on weathered surfaces.

The major channelized sandstones (C-8) are comparable with the very thick sandstones of the Gibbett Hill Formation (Signal Hill Group). Although exposures are too small to determine the geometry of the sand bodies, they have been observed at widespread localities.

### *Structural Relations and Correlation*

The Renews Head Formation is the lowest *in situ* stratigraphic unit on the west limb of the Blackhead Syncline. However, between Outer and Middle coves it appears to be structurally repeated. Facies A-8, present on the east side of Outer Cove is overlain by facies B-8 and C-8 further east (i.e., towards Torbay Point); comparable facies associations also occur between the west side of Outer Cove and the northeast side of Middle Cove. A major cycle (ABC ABC) has not been observed elsewhere in the region, therefore it is assumed that there is a fault in Outer Cove, which repeats the formation.

The Renews Head Formation correlates with Hutchinson's (1953) upper part of the Carbonear Formation in western Conception Bay.

# SIGNAL HILL GROUP (UNITS 9 to 13)

## Definition

Alluvial plain conditions developed across the Avalon Zone, by latest Vendian time, in response to a major uplift (north of the present Bonavista and Avalon peninsulas) related to the Avalonian Orogeny. This period is represented by molasse-like clastic rocks of the Signal Hill Group on the Avalon Peninsula and by parts of the volcanic and clastic successions that comprise the Musgravetown Group and equivalents further west (Figure 5). The former Signal Hill Formation (Rose, 1952) with its type section at Signal Hill, corresponds with the original 'Signal Hill Sandstone' of Jukes (1843), the 'Signal Hill formation' of Murray and Howley (1881a, b), and the 'Signal Hill Series' of Buddington (1919). In the type area, the St. John's and Signal Hill formations were defined as two of three formations of the Cabot Group (Rose, 1952). Both formations have since been elevated to group status and the name Cabot has been abandoned (Williams and King, 1979). Major stratigraphic nomenclatural revisions are shown in Table 1.

The Signal Hill Group now includes four distinct, mappable units of formational status within the type area. In ascending order, these are the Gibbett Hill, Quidi Vidi, Cuckold and Blackhead formations (Figure 6). All occur in the eastern part of the map area (Figure 15). A composite stratigraphic section of the Signal Hill Group is shown in Figure 16. Massive beds of Cuckold conglomerate on the eastern limb of the Blackhead Syncline at Cape Spear National Historic Park, represent the most easterly onshore formation in the Appalachians of North America.

In the eastern Avalon Peninsula, the Signal Hill Group has a maximum exposed thickness of 5 km and extends from Flat Rock to Cape Ballard (Figure 3). The Flat Rock Cove, Cappahayden, Ferryland Head, and Cape Ballard formations are facies variations (Figure 6). A comparable belt of rocks in the western Avalon Peninsula extends from Grates Cove to Cape St. Mary's (Figure 3).

The Signal Hill Group is gradational with the underlying St. John's Group in the northeastern Avalon Peninsula. In the southeastern Avalon Peninsula, the top of the Renews Head Formation (St. John's Group), is marked by an erosional disconformity and overlain by the Cappahayden Formation, which is conformably overlain by the Gibbett Hill Formation (Figure 6). The upper boundary of the Signal Hill Group is not exposed in the eastern Avalon Peninsula. A correlative of the Signal Hill Group, the Musgravetown Group, is unconformably overlain by the Lower Cambrian Random Formation (Figures 3, 5 and 6).

## Gibbett Hill Formation (Unit 9)

### *Name, Distribution and Thickness*

Gibbett Hill, a prominent landmark (Plate 28) on Signal Hill was given its name by the British in 1750, because victims of judicial hangings were exhibited there on a gibbett. Quarries which operated here in the past, supplied material for foundations, bridge abutments, retaining walls, and for the old fortifications, including Fort William, built in the 1690's to defend against the French. The hill, which is the type section of the Gibbett Hill Formation (King, 1972a; revised by Williams and King, 1979), is a 375-m-thick unit of buff-weathering sandstones that are greenish grey on fresh surface. It equates with the 'Signal Hill Grey Sandstone' (map unit 'e') of Murray and Howley (1881a, b, 1918) and Rose's (1952) lower unnamed member of the 'Signal Hill Formation' (Table 1). The original type locality of the 'grey sandstone' is Gibbett Hill (Jukes, 1843, Murray and Howley, 1881a).

The Gibbett Hill Formation can be traced in virtually continuous outcrop for 110 km, in the eastern Avalon Peninsula (Figure 6). The formation is about 100 m thick at Knobby Hill (Flat Rock) and slightly more at Torbay Point (north of St. John's); it gradually increases to about 500 m in the Signal and Southside hills, 750 m near Petty Harbour Long Pond, reaches a maximum thickness of 1500 m near Bay Bulls and from there gradually decreases to about 750 m at Cape Ballard. In the map area it forms part of the steeply eastward dipping limb of the Blackhead Syncline.

### *Lithology*

The Gibbett Hill Formation in the map area consists of two main lithofacies, which subdivide the formation into two parts (Figure 16):

> Facies A-9 consists of medium to thick, laterally persistent beds of buff-weathering, greenish-grey sandstone, interbedded locally with greenish-grey siltstone and grey conglomerate and occurs mainly in

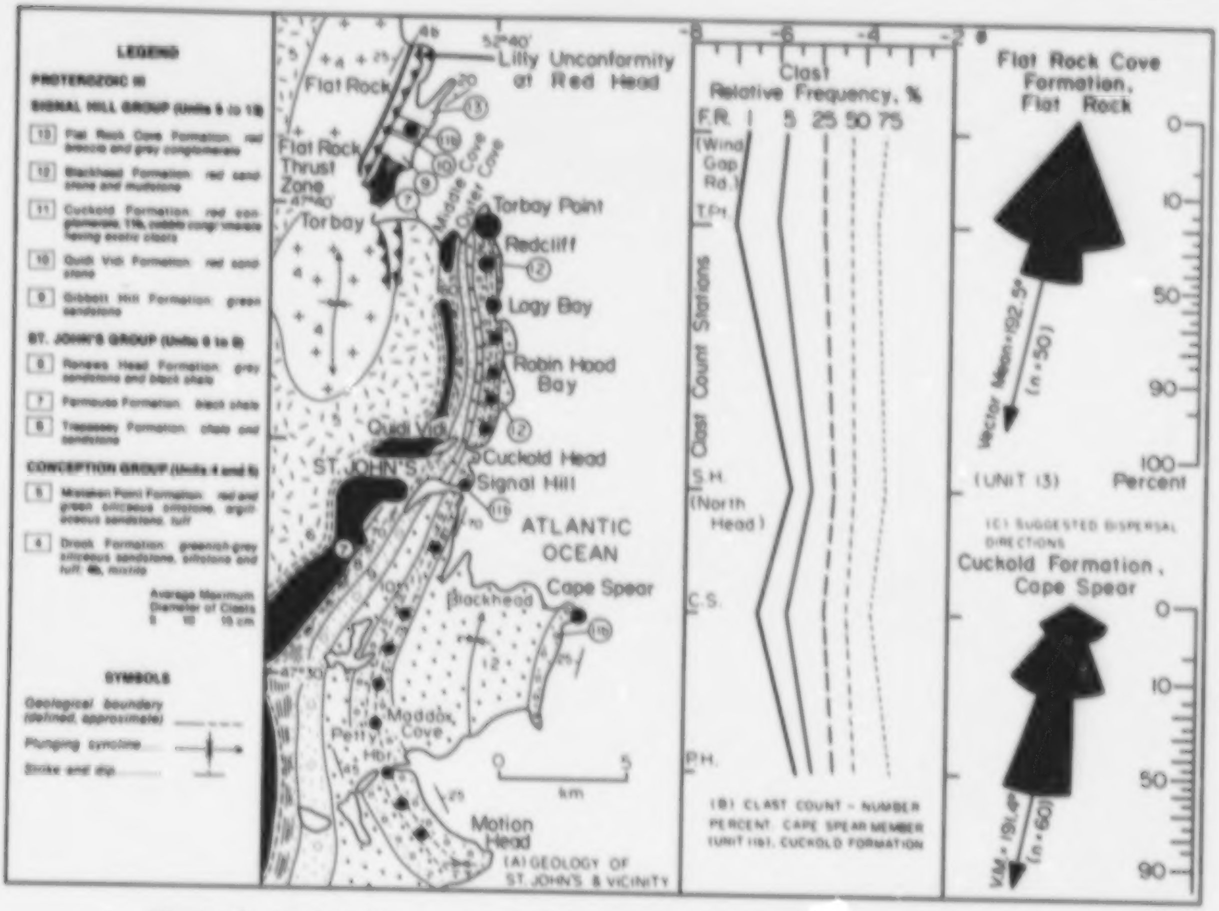

LEGEND
PROTEROZOIC III
SIGNAL HILL GROUP (Units 9 to 13)
13 Flat Rock Cove Formation: red breccia and grey conglomerate
12 Blackhead Formation: red sandstone and mudstone
11 Cuckold Formation: red conglomerate; 11b, cobble conglomerate having exotic clasts
10 Quidi Vidi Formation: red sandstone
9 Gibbett Hill Formation: green sandstone
ST. JOHN'S GROUP (Units 6 to 8)
8 Renews Head Formation: grey sandstone and black shale
7 Fermeuse Formation: black shale
6 Trepassey Formation: shale and sandstone
CONCEPTION GROUP (Units 4 and 5)
5 Mistaken Point Formation: red and green siliceous siltstone, argillaceous sandstone, tuff
4 Drook Formation: greenish-grey siliceous sandstone, siltstone and tuff; 4b, mixtite
Average Maximum Diameter of Clasts
5 10 15 cm
SYMBOLS
Geological boundary (defined, approximate)
Plunging syncline
Strike and dip
52°40'
Lilly Unconformity at Red Head
Flat Rock
Flat Rock Thrust Zone
47°40'
Torbay
Middle Cove
Outer Cove
Torbay Point
Redcliff
Logy Bay
Robin Hood Bay
Quidi Vidi
ST. JOHN'S
Cuckold Head
Signal Hill
ATLANTIC OCEAN
Blackhead
Cape Spear
Maddox Cove
Petty Hbr.
Motion Head
0 5 km
(A) GEOLOGY OF ST. JOHN'S & VICINITY
-8 -6 -4 -2 Φ
Clast Relative Frequency, %
F.R. 1 5 25 50 75
(Wind Gap Rd.)
T.Pt.
Clast Count Stations
S.H. (North Head)
C.S.
P.H.
(B) CLAST COUNT - NUMBER PERCENT: CAPE SPEAR MEMBER (UNIT 11b), CUCKOLD FORMATION
Flat Rock Cove Formation, Flat Rock
Vector Mean = 192.5° (n = 50)
0 10 50 90 100
(UNIT 13) Percent
(C) SUGGESTED DISPERSAL DIRECTIONS
Cuckold Formation, Cape Spear
V.M. = 191.4° (n = 60)
0 10 50 90

**Figure 15.** *Geological map and sedimentary features of the eastern St. John's study area.*

the lower part of the formation. Small-scale scour and fill structures, planar (alpha) and trough (theta) cross-bedding, rip-up clasts and internal loads are common features in the sandstones. The siltstones show parallel- and cross-laminations, grading and mud cracks. Possible trace fossils were found in the siltstones exposed in roadcuts on the east side of St. John's Harbour; groove-like markings, up to 2 cm in width, were either made by organisms foraging along the bottom or by clasts sliding over a wet, soft substrate.

Facies B-9 occurs in the upper part of the formation and consists mainly of very thickly bedded (up to 15 m thick) massive sandstone. However, despite the homogeneous appearance, a wide variety of structures and textures is present. Careful examination reveals parallel laminations (Plate 29), amalgamation of multiple beds, thin tuffs, mud flake breccia beds, loading, large spherical sandstone balls (due to diagenesis), primary current lineations, sandstone dykes and trough (theta, pi) cross-stratification. Excellent examples of this rock type can be seen at Gibbett Hill (Plate 28), the Lower Battery (north of St. John's harbour), and on the grounds of the Northwest Atlantic Fisheries Centre (White Hills). Medium to thick grey sandstones of this facies are locally interfingered with red sandstones and mudstones (e.g., in Lundrigan's Quarry, White Hills).

Thin sections of the medium- to coarse-grained sandstone from the Gibbett Hill Formation, show that they are lithofeldspathic to arkosic in composition. They are moderately well sorted with angular to subrounded clasts of quartz (20 to 35 percent), lamellar twinned albite (15 to 30 percent), orthoclase–microcline (5 to 15 percent), rock fragments (5 to 25 percent) and groundmass (15 percent). Rock fragments include rhyolite, tuff, altered basalt, granophyre, siltstone and quartzite. The groundmass consists of fine grains of quartz, feldspar and rock fragments with minor amounts of devitrified glass shards, sericite, chlorite, biotite, magnetite, calcite, and traces of detrital zircon, sphene and epidote. Authigenic or secondary growths of quartz have substantially reduced the porosity and permeability of the rock.

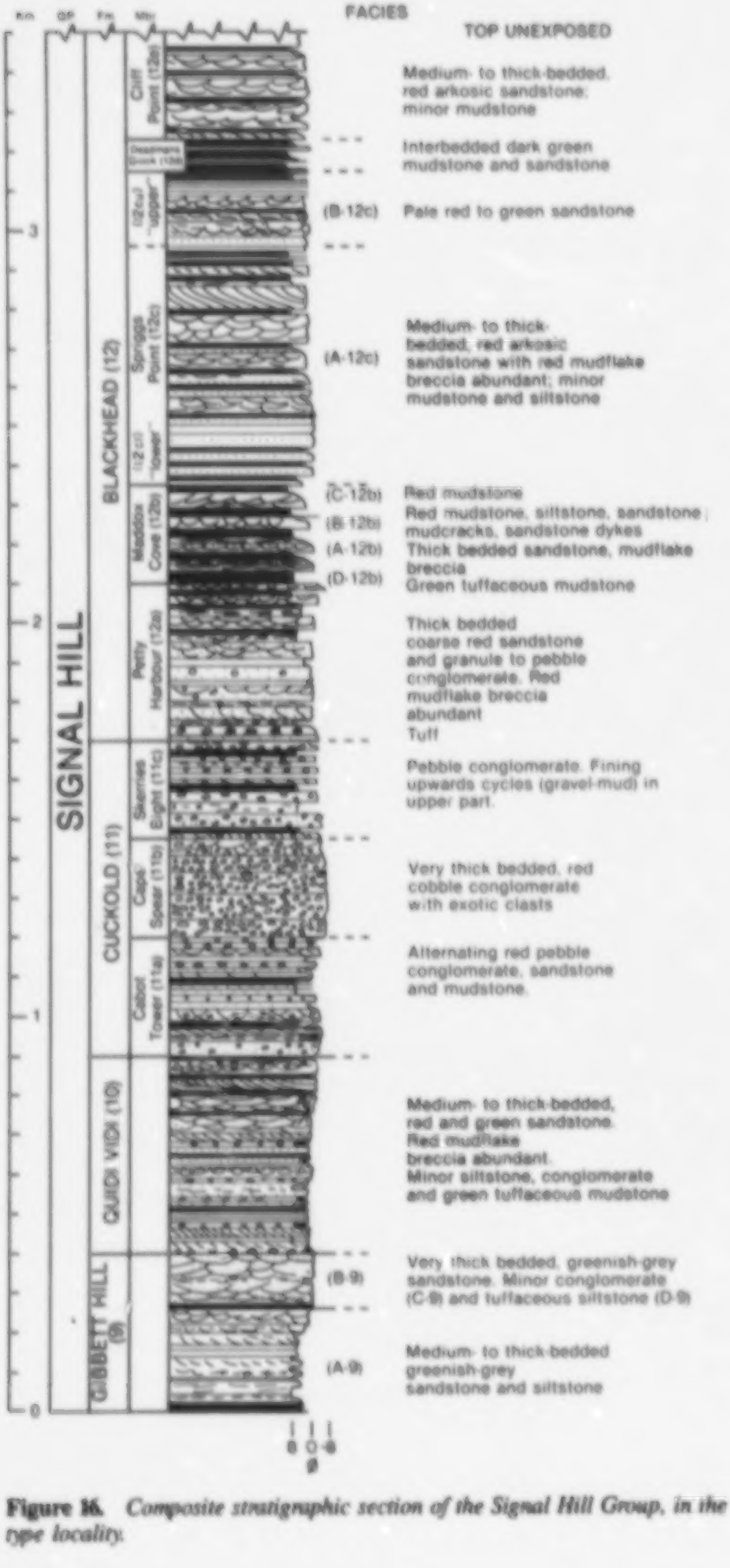

Km
GP
Fm
Mbr
FACIES
TOP UNEXPOSED
3
2
1
0
SIGNAL HILL
BLACKHEAD (12)
CUCKOLD (11)
QUIDI VIDI (10)
GIBBETT HILL (9)
Cliff Point (12e)
Deadmans Brook (12d)
(12c) "upper"
Spriggs Point (12c)
(12c) "lower"
Maddox Cove (12b)
Petty Harbour (12a)
Skerries Bight (11c)
Cape Spear (11b)
Cabot Tower (11a)
Medium- to thick-bedded, red arkosic sandstone; minor mudstone
Interbedded dark green mudstone and sandstone
(B-12c) Pale red to green sandstone
(A-12c) Medium- to thick-bedded, red arkosic sandstone with red mudflake breccia abundant; minor mudstone and siltstone
(C-12b) Red mudstone
(B-12b) Red mudstone, siltstone, sandstone; mudcracks, sandstone dykes
(A-12b) Thick bedded sandstone, mudflake breccia
(D-12b) Green tuffaceous mudstone
Thick bedded coarse red sandstone and granule to pebble conglomerate. Red mudflake breccia abundant
Tuff
Pebble conglomerate. Fining upwards cycles (gravel-mud) in upper part.
Very thick bedded, red cobble conglomerate with exotic clasts
Alternating red pebble conglomerate, sandstone and mudstone.
Medium- to thick-bedded, red and green sandstone. Red mudflake breccia abundant. Minor siltstone, conglomerate and green tuffaceous mudstone
(B-9) Very thick bedded, greenish-grey sandstone. Minor conglomerate (C-9) and tuffaceous siltstone (D-9)
(A-9) Medium- to thick-bedded greenish-grey sandstone and siltstone
8
0
-8
φ

**Figure 16.** *Composite stratigraphic section of the Signal Hill Group, in the type locality.*

Numerous fractures or joints can be seen on top of Gibbett Hill and near the entrance to Signal Hill National Historic Park. The fractures dip 20 to 30°N and are filled with milky quartz, very pale green to milky white prehnite, minor calcite and also occasional traces of copper minerals.

Two other lithofacies are locally well developed within the Gibbett Hill Formation. East of the Goulds, poorly exposed grey pebble conglomerate (facies C-9) is interbedded with thick sandstone of the Gibbett Hill Formation. It is composed of subrounded pebbles and granules of quartz, perthitic feldspar, rhyolite, chert and intraformational fragments of black shale. East of Lundrigan's Quarry in the White Hills, minor interbeds of yellow-green tuffaceous siltstone (facies D-9) occur in the upper part of the formation. Devitrified y-shaped shards are recognizable in a very fine grained highly altered groundmass. It is noteworthy that major tuff bands (2 to 5 m thick) are present in the middle part of the Gibbett Hill Formation at Bay Bulls, Mobile Bay and Ferryland (Hsu, 1972).

### *Contact Relations*

The base of the Gibbett Hill Formation in the map area is arbitrarily drawn, where lenticular bedded sandstones and shales of the Renews Head Formation grade upward into medium- to thick-beds of dominantly grey, tuffaceous sandstone; this gradational zone is poorly exposed and is assumed to be less than 30 m thick. In the type section, the base is taken opposite the northern corner of the former U.S. Airforce Dock, north St. John's Harbour (Map sheet 1254). A thin breccia bed, consisting of angular fragments of green siltstone having glass shards in the matrix, occurs on the east side of Gibbett Hill and defines a sharp, erosional boundary with the overlying Quidi Vidi Formation.

### *Correlation*

The Gibbett Hill Formation correlates with the Halls Town Formation of Hutchinson (1953), an 850- to 1500-m-thick unit within the Harbour Grace map area of western Conception Bay. Rocks of the Halls Town Formation were originally included within the 'Signal Hill Grey Sandstone' of Murray and Howley (1881a, b, 1918). King (1988) replaced the name

**Plate 28.** *Aerial view of Gibbett Hill, Signal Hill National Historic Park, type section of Gibbett Hill Formation. (Photograph courtesy of Ben Hansen)*

**Plate 29.** *Low-angle planar cross-stratification in Gibbett Hill Formation.*

Halls Town by the name Gibbett Hill Formation; but retained the type and other sections designated by Hutchinson (1953, p. 14-16) as principal reference sections.

## Quidi Vidi Formation (Unit 10)

### *Name, Distribution, Thickness and Correlation*

Red sandstones and mudstones of the formation were included in the 'Signal Hill Sandstone' of Jukes (1843) and described as the 'Signal Hill Red Sandstone' (unit f) by Murray and Howley (1881a, b). Buddington (1919) considered the rocks to be part of the 'Signal Hill Series'. Rose (1952) termed it the middle unnamed member in the 'Signal Hill Formation'. This member, informally termed the 'Battery Member' (King, 1972a), was subsequently named the Quidi Vidi Formation by King (1980, 1982) after the Signal Hill Formation was elevated to Group status by Williams and King (1979).

King (1980, 1982) designated Quidi Vidi Village as the type locality; the type section (Plate 30) is defined in steep cliffs along the north side of Quidi Vidi Harbour, commencing approximately 90 m east of the bridge at the east end of Quidi Vidi Lake and terminating about 30 m west of a small unnamed pond (northwest of the breakwater). Reference sections are designated along the north and south sides of St. John's Narrows and Blackhead Road (Shea Heights).

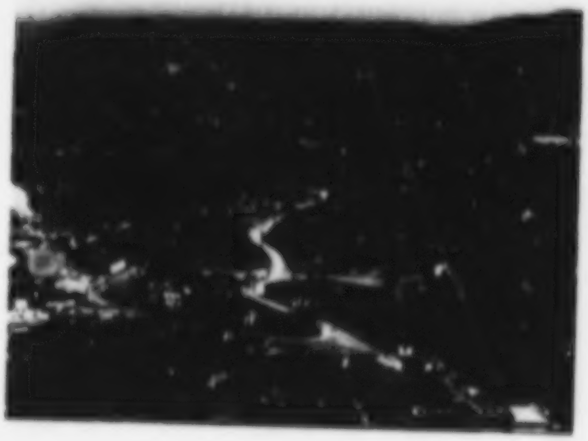


**Plate 30.** *Type locality of Quidi Vidi Formation (north side of Quidi Vidi Harbour) and Cuckold Formation (Cuckold Head, east of breakwater). (Photograph courtesy of Ben Hansen)*

The Quidi Vidi Formation at Flat Rock is about 125 m thick and gradually thickens southward to about 275 m in the type section; its estimated thickness is 500 m east of St. John's Harbour, 1100 m east of the Goulds and about 1000 m in the Bay Bulls–Witless Bay area (Figure 6). Correlatives on the Avalon Peninsula are shown in King (1988). The Ferryland Head Formation (Williams and King, 1979) of Trepassey area is presumed to be at least a partial facies equivalent (Figure 6). Red arkosic sandstone and pebble conglomerate of the Bay de Verde Formation (O'Driscoll and King, 1985) in northwestern Conception Bay are included within the Signal Hill Group (King, 1988).

### *Lithology*

The Quidi Vidi Formation is composed of medium to thick beds of red arkosic sandstone having thin to medium interbeds of siltstone, mudstone, intraformational breccia, red conglomerate and green sandstone. Interbeds of tuffaceous mudstone and siltstone, up to 1 to 2 m thick, occur locally (e.g., east of Lundrigan's White Hills quarry, and the Sugar Loaf Pond area). The sandstones have sharp, planar to bulbous erosional bases, and commonly show medium- to large-scale trough (theta, pi) crossbeds, parallel lamination, convolute lamination, rip-up clasts of red mudstone, mud flake breccia, injection breccias, sand dykes, and internal loading (Plate 31); fining-upward sequences consisting of thick sandstone passing up into parallel- and ripple-laminated siltstone and mudstone are locally well developed. Red mudstone and laminated siltstone units, up to 2 m thick, commonly show sand-filled polygonal mudcracks, brecciated tops, sandstone dykes and sills, soft-sediment faults, load structures, and scours filled with sandstone.

**Plate 31.** *Thixotropic deformation in Quidi Vidi Formation, Petty Harbour Road.*

Thin sections of fine- to medium-grained sandstones from the Quidi Vidi Formation show they are arkosic in composition. They are moderately sorted with angular to subrounded clasts of quartz (30 to 35 percent), plagioclase feldspar (20 to 25 percent), orthoclase feldspar (<15 percent), rock fragments (15 to 20 percent) and groundmass (20 percent). Rock fragments are similar in composition to those in the Gibbett Hill Formation, but are dominated by felsic volcanic rocks. Finely disseminated hematite surrounds the grains, fills the interstices and gives the rock its red colour. Comparisons of the ferrous and ferric contents of the red (Quidi Vidi) and green (Gibbett Hill) sandstones (Table 5) show that although both have similar contents of iron (approximately 5 percent), the red sandstones have 4.75 percent of ferric oxide and only 0.46 percent ferrous oxide, whereas the green sandstones have 2.54 percent of ferric oxide and 2.82 percent of ferrous oxide (Buddington, 1916).

### *Contact Relations*

Dominantly fine- to medium-grained, red, arkosic sandstones, comprising the southward thickening Quidi Vidi Formation are exposed in the eastern perimeter of the map area, where they dip steeply eastward and form the western limb of the Blackhead Syncline (Figures 7 and 15). The lower beds of the formation are generally in sharp, erosional contact with the underlying Gibbett Hill Formation. The upper boundary with the overlying Cuckold Formation is gradational.

## Cuckold Formation (Unit 11)

### *Name, Distribution and Thickness*

The red arkosic sandstones of the Quidi Vidi Formation gradually pass upwards into the overlying red conglomerate and arkose of the Cuckold Formation. This unit was first described by Jukes (1843) who included coarse grained conglomerate within the Signal Hill Sandstone (Table 1). Murray and Howley (1881a, b) included it within their Signal Hill red conglomerate and sandstone (map unit g). King (1972a) proposed the name Cuckold Member for the unnamed upper member of the Signal Hill Formation of Rose (1952). He designated the type locality as Cuckold Head (Plate 30). After elevation of the Signal Hill Formation to group status by Williams and King (1979), the Cuckold Member was subsequently elevated to Cuckold Formation by Hofmann *et al.* (1979). This formation is well exposed in the eastern part of the map area and extends from Flat Rock to Petty Harbour.

### *Lithological Subdivisions*

The Cuckold Formation in its type section on the northern side of Quidi Vidi Harbour and southwestern Skerries Bight, is about 800 m thick; it is divisible into three members, which in ascending order are Cabot Tower, Cape Spear and Skerries Bight (Figure 16). As there are no local place names in the western part of the type section, the name Cabot Tower is used. Skerries Bight (termed Sherries Bight on 1:12,500 maps) is a small cove, north of the entrance to Quidi Vidi Harbour.

### *Structural Relations*

The conglomerates of the Cuckold Formation form part of the western limb of the Blackhead Syncline and reappear on the eastern limb at Cape Spear National Historical Park (Figure 15). Within the trough of the Blackhead Syncline are red and grey sandstones and mudstones of the Blackhead Formation, which is the highest stratigraphic unit within the

St. John's region. Bedding-plane faults occur within the Cuckold Formation at South Side, Signal and White hills; the amount of tectonic omission or repetition of beds is unknown but is assumed to be minimal. Boundary relations in the type section of the Cuckold Formation are generally representative of the formation throughout the map area.

### *Correlation*

The Cuckold Formation conglomerates wedge out to the south by passing into a red sandy facies near Bay Bulls that resembles both the Quidi Vidi and Blackhead formations (Figure 6). These combined units at Ferryland, about 60 km south of the type section, are termed the Ferryland Head Formation (Williams and King, 1979). The Cuckold Formation is a correlative of the Baccalieu Member (Bay de Verde Formation) of northern Conception Bay (King, 1988).

### *Cabot Tower Member (Subunit IIa)*

*Name, Distribution and Thickness.* The Cabot Tower Member lies to the east of the Quidi Vidi Formation (in the type section), where it is about 275 to 300 m thick. The name of the member, which is formally proposed here, is derived from a principal reference section designated in the Cabot Tower area of Signal Hill National Historic Park; the section is between the eastern end of Queen's Battery (the name dating back to the Napoleonic Wars) to Ladies' Lookout (site of a blockhouse, 1795) and continues below the summit to Ross's Valley and Soldier's Gulch. Cabot Tower, a prominent structure, was built between 1897 and 1900 of conglomerate and sandstone. An alternative reference section is along the Narrows trail between Fort Chain Rock (dating back to the 1690's) and North Head; the base of the member is approximately 150 m east of World War II installations at Fort Chain Rock and the top is 125 m west of North Head beacon (Plate 32). The distribution of the member is shown in Figure 7.

*Lithology.* The Cabot Tower Member, in contrast with the massive appearance of the Quidi Vidi Formation, consists of alternating medium- to thick-beds of red pebble conglomerate, variegated (red, white, purple, green) sandy conglomerate and coarse sandstone, and medium units of red mudstone (Figure 16). The coarse clastic beds show trough (theta, pi) and planar (alpha, omikron) cross-bedding, loading, and rip-up clasts of red mudstone.

The clast content of the Cabot Tower Member is fairly constant throughout the map area. Subrounded to well-rounded pebbles and granules of rhyolite, rhyolite porphyry, and ignimbrite comprise 75 to 85 percent of the coarse fraction and are comparable with Harbour Main felsic volcanic rocks. Subangular to subrounded clasts of granite and granophyre (Holyrood Intrusive Suite?) typically comprise 1 to 5 percent but locally as much as 10 percent; in thin section, the granophyre shows graphic intergrowth between quartz and perthitic microcline. Clasts of siliceous sedimentary rocks (chert, argillite, tuffite) representative of the Conception Group are always present; they generally form 5 to 10 percent, but locally up to 30 percent of the coarse fraction. Mafic fragments (basalt, diorite) are rare. Locally reworked angular fragments of sandstone and mudflakes are common, but are not included in estimates of percentage.

**Plate 32.** *Principal reference section of Cabot Tower Member (Cuckold Formation) on north side of Narrows between Cabot Tower and prominent gulch east of North Head. Cape Spear Member occurs to right of gulch and at Fort Amherst Lighthouse (foreground). (Photograph courtesy of Ben Hansen)*

*Contact Relations.* The Cabot Tower Member gradationally overlies the Quidi Vidi Formation throughout the map area. A gradational zone, about 10 m wide in the Torbay Point area, gradually increases to about 100 m or more on the north shore of Petty Harbour First Pond. Master bedding planes, well exposed on the South Side Hills, were traced southward and used to assist definition of the lower boundary of the formation, particularly in areas of poor exposure. An arbitrary boundary is drawn where conglomerate comprises more than 50 percent of the sequence. South of Petty Harbour First Pond, the Cabot Tower Member passes from granule conglomerate into very coarse sandstone; the boundary with the Quidi Vidi Formation is very diffuse and the two formations are presumed to merge offshore Bay Bulls (Figure 6).

### *Cape Spear Member (Subunit IIb)*

*Name, Distribution and Thickness.* The type locality of the Cape Spear Member (King, 1982) is to the east of the gun sites at Cape Spear National Historic Park (Plate 33); sea cliffs here form the most easterly point in North America (access to the cliffs is now restricted by Parks Canada). As shown in Figures 7 and 15, the Cape Spear Member extends southward to North Head, Motion Bay (not to be confused with North Head, St. John's Narrows). Between Broad Cove and Empty Basket Cove, the exposed thickness of the unit is 125 m (the base extends below sea level).

The Cape Spear Member, (in the type section of the Cuckold Formation), consists of approximately 250 m of distinctive cobble conglomerate (Figures 16 and 17). A gradational boundary with the Cabot Tower Member is placed about 70 m southwest of a prominent gulch (a possible

**Plate 33.** *Westward-dipping cobble conglomerate of Cape Spear Member, east of Cape Spear Lighthouse.*

bedding-plane fault) at the entrance to Quidi Vidi Harbour. Cuckold Head is composed entirely of this member.

The Cape Spear Member extends from Torbay Point to south of Motion Bay; it is also present at Knobby Hill (Flatrock) where it is less than 50 m thick (Figures 18 and 19). Although the member is well exposed in the type localities at Cape Spear and Quidi Vidi, access to the eastern half of the member, at both localities, is difficult because of marine conditions and sheer cliffs. The Cape Spear section is virtually identical to the Logy Bay section and the two are presumed correlatives. A principal reference section is therefore designated in Logy Bay; the base of the member is taken along Logy Bay Road, 150 m west of the southwestern corner of Logy Bay, and the top in a small cove about 150 m west of the Ocean Sciences Centre (Plate 34). Good exposures also occur at Torbay Point (difficult access), a ridge east of Soldier's Gulch (easy access via path from Signal Hill) and at South Head, Fort Amherst (easy access to lower half of member).

*Lithology.* Gently westward dipping cobble conglomerates, which form the Cape Spear to North Head (Motion Bay) coastal cliffs (Plate 33), contain distinctive exotic clasts of quartz–sericite schist, quartzite and other low-grade metamorphic rocks (Figure 16); these clasts locally form between 10 and 25 percent of the coarse fraction and may indicate a sialic basement source. The size and bulk composition of the clasts and matrix is comparable with that of the Logy Bay section (Plates 34 and 35). Red to purple cobbles of rhyolite, rhyolite porphyry and ignimbrite predominate. Clusters of coarse granitoid cobbles are locally common but seldom exceed 25 percent of the coarse fraction. Diffuse interbeds of pebbly sandstone show large scale (0.5 to 1 m high) trough (theta, pi) crossbeds with a unimodal paleoflow to the south-southwest (Figure 15). Interbeds of thin, red dessicated mudstones increase in frequency towards the southern part of the belt (e.g., Empty Basket Cove); they show abundant scours having ubiquitous mudflake breccia and sandstone fill. Load structures and sandstone dykes attest to the liquefied state of the sands shortly after their deposition.

Clast/matrix ratios vary considerably even in individual localities. However, the maximum diameter of clasts in the Cape Spear and Cabot Tower members shows a gradual southward decrease in size. Lateral variations for the Cape Spear Member are shown in Figure 15; the largest clasts (up to 28 cm, i.e., small boulder) occur mixed with abundant cobbles east of Torbay Point, and gradually decrease to small cobble size south of Petty Harbour.

Clasts of similar lithology within the Cape Spear Member show a mildly progressive increase in roundness and sphericity from Torbay Point to Petty Harbour. Granitic clasts, for example, are blocky, equant and subangular to subrounded in the north; 15 km to the south they have high sphericity and are rounded. However, it is clear that rapid reduction in size of clasts is due largely to fragmentation and spalling; rounded clasts with fractured, angular faces are common. Matrix grains show rounding by attrition.

*Contact Relations.* The Cape Spear Member conformably overlies the Cabot Tower Member and has a gradational contact. The gradational zone is several metres wide in the type section at Quidi Vidi and gradually increases to about 25 m at the northern end of Petty Harbour First Pond. A comparable gradational zone separates the Cape Spear Member from the Skerries Bight Member.

In the type locality at Cape Spear, the lower boundary of the Cape Spear Member is below sea level. Between Cape Spear and North Head, the upper boundary is along the highest part of the cliff, which in places is close to 100 m a.s.l. It is in gradational contact with a 250-m-thick unit of trough cross-stratified sandy conglomerate, which is assumed to be a correlative of the Skerries Bight Member.

At Knobby Hill in Flatrock (Figure 18), the Cape Spear Member with its exotic clasts appears to be conformably or disconformably overlain by grey conglomerate of the Flat Rock Cove Formation (Unit 13). However, the age of the Flat Rock Cove Formation is uncertain and it may be Paleozoic (King, 1980).

### *Skerries Bight Member (Subunit IIc)*

*Name, Distribution and Thickness.* Skerries Bight (also known as Sherries Bight) is a small cove between Quidi Vidi Harbour and Small Point. A cart track leads to the Bight from the Northwest Atlantic Fisheries Centre. The lower contact of the Skerries Bight Member with the Cape Spear Member is conformable; in the type section it is located 750 m north of the Quidi Vidi Gut breakwater and is only accessible by boat. The upper boundary is adjacent to the Fisheries Centre pumping station at the Bight. The estimated thickness of the Skerries Bight Member in the type section is 250 m.

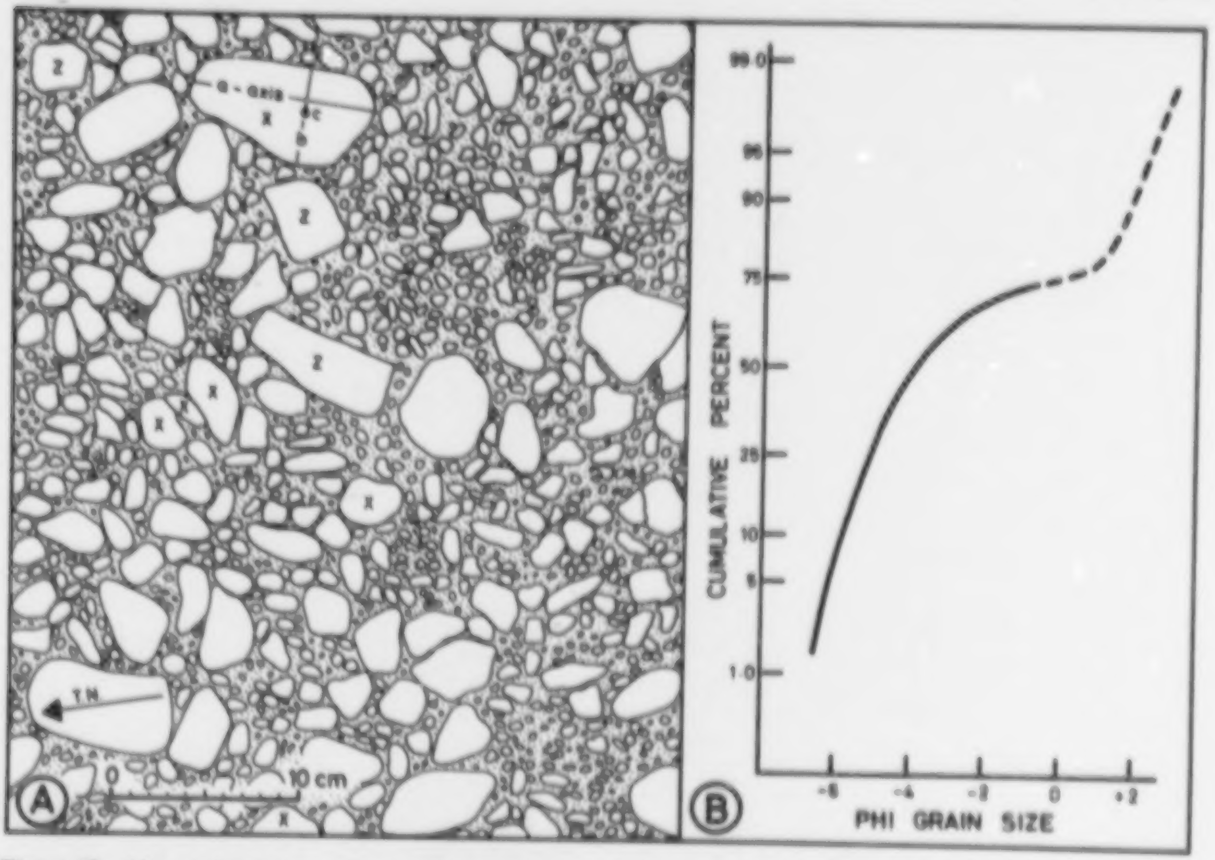


**Figure 17.** *Clast and matrix variations in the Cape Spear Member, Cuckold Formation, Cape Spear. (A). Plan view of conglomerate bedding surface showing clasts of rhyolite, tuff, quartz sericite–schist (x), and vein quartz (z) in a poorly sorted matrix. C-axis of largest clast is approximately 4 cm. (B). Grain-size cumulative curve for coarsest stratigraphic level in Cape Spear Member, Sample area 2 m² by 5 cm thick.*

The Skerries Bight Member is sporadically exposed in very steep coastal cliffs between Torbay Point and Petty Harbour (Figure 15). This unit forms the photogenic cliffs above Sculpins Point, northern Logy Bay and underlies the Marine Sciences Research Laboratory on the southern side of the bay. Good exposures occur at the eastern end of St. John's City Dump (Robin Hood Bay). Apart from the outcrops at the Marine Sciences Research Laboratory, the only readily accessible exposures of the member are along Blackhead Road (750 m west of Leamy's Brook) and north of Petty Harbour Power Station.

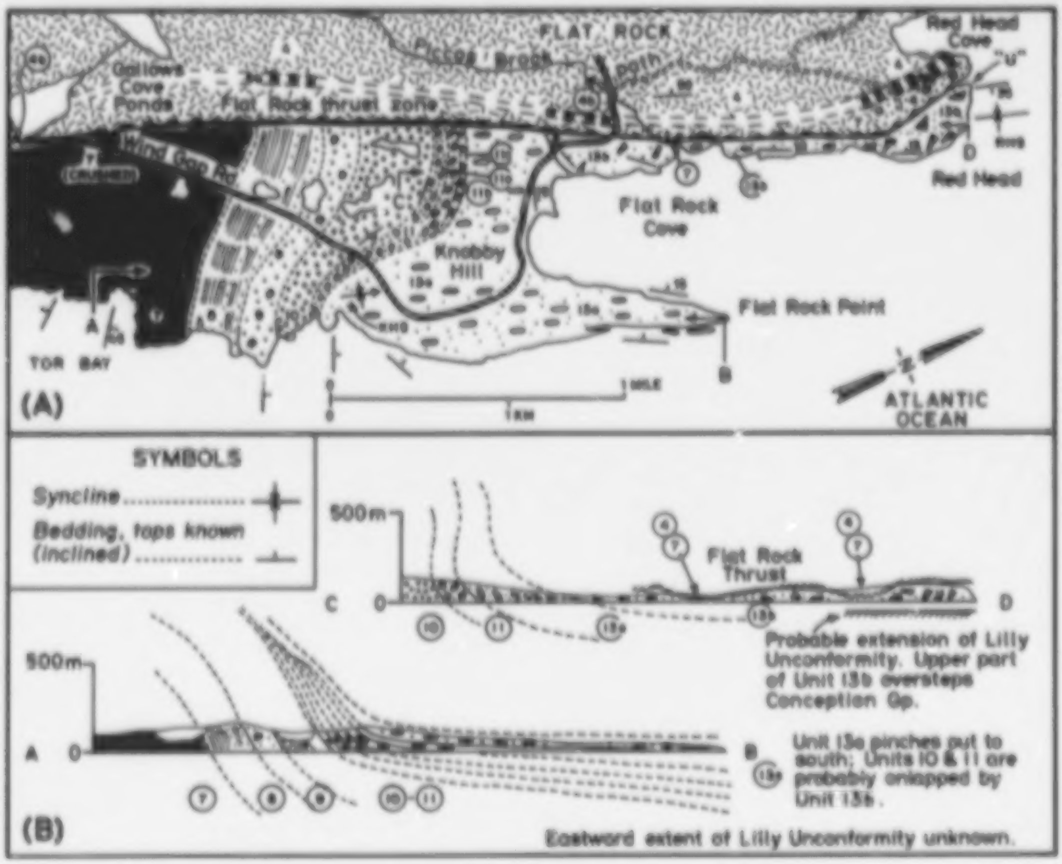
*Lithology.* In the type section of the Cuckold Formation, the Skerries Bight Member is generally comparable with the Cabot Tower and Cape Spear members in composition, texture and structure. It differs in that, (i) the lower half of the member shows much greater lateral and vertical fluctuations in clast sizes than the underlying two members, indicating greater variations (possibly cyclic) in downstream river flow regime; (ii) the upper part shows fining upwards cycles (e.g., gravel bedforms–foreset gravel/sandbeds–sandy cross-stratified beds–siltstones–mudstones); and (iii) bed thickness and grain size decrease whereas red mudstone interbeds increase in frequency and thickness upwards in the succession.

*Contact Relations.* The Skerries Bight Member gradationally overlies the Cape Spear Member. In near vertical cliffs at Skerries Bight, the Skerries Bight Member progressively fines upward through a 50-m-wide gradational zone into arkosic sandstone and mudstone of the overlying Blackhead Formation. In the Petty Harbour area, the gradational zone is about 100 m wide.

## Blackhead Formation (Unit 12)

### *Name, Distribution, Thickness and Correlation*

The name 'Blackhead' was first used by Hayes (1931) in reference to the rocks at Blackhead, east of St. John's, and described by him as 'dark grey sandstone and slates'. The formational name was applied by Rose (1952) for 'the sedimentary rocks that lie immediately and conformably above the Signal Hill conglomerate and that are found in the core of a syncline in these rocks at Black Head'.


FLAT ROCK
Piccos Brook
path
Gallows Cove Ponds
Flat Rock thrust zone
Wind Gap Rd
CRUSHER
Red Head Cove
"u"
RHS
D
Red Head
Flat Rock Cove
Knobby Hill
13a
13b
KHS
Flat Rock Point
A
B
TOR BAY
(A)
0
1 MILE
1 KM
ATLANTIC OCEAN
SYMBOLS
Syncline
Bedding, tops known (inclined)
500m
0
C
D
Flat Rock Thrust
4
7
10
11
13a
13b
Probable extension of Lilly Unconformity. Upper part of Unit 13b oversteps Conception Gp.
500m
A
0
B
7
8
9
10-11
Unit 13a pinches out to south; Units 10 & 11 are probably onlapped by Unit 13b.
(B)
Eastward extent of Lilly Unconformity unknown.

## LEGEND

**SIGNAL HILL GROUP (UNITS 9 TO 13)**

| 13 | FLAT ROCK COVE FORMATION: *conglomerate, breccia, sandstone and mudstone;* 13a, Knobby Hill Member: *grey pebble conglomerate and sandstone;* 13b, Piccos Brook Member: *locally derived breccia, conglomerate, red sandstone and mudstone*

| 11 | CUCKOLD FORMATION: *Red conglomerate and sandstone;* 11a, Cabot Tower Member: *red pebble conglomerate and sandstone;* 11b, Cape Spear Member: *red cobble conglomerate with exotic clasts;* 11c, Skerries Bight Member: *red pebble conglomerate and sandstone*

| 10 | QUIDI VIDI FORMATION: *Red sandstone and mudstone*

| 9 | GIBBETT HILL FORMATION: *Greenish-grey sandstone*

**ST. JOHN'S GROUP (Units 7 and 8)**

| 8 | RENEWS HEAD FORMATION: *Lenticular-bedded grey sandstone and shale*

| 7 | FERMEUSE FORMATION: *Grey to black shale*

**CONCEPTION GROUP (Unit 4)**

| 4 | DROOK FORMATION: *Greenish-grey siliceous sandstone, siltstone and tuff;* 4b, Bauline Line Member: *volcanogenic mixtite*

▨ locally derived breccia; red muddy sandstone

▨ grey conglomerate and sandstone

▨ conglomerate containing exotic pebbles

▨ red conglomerate and sandstone

▨ red sandstone

▨ grey sandstone

▨ grey rippled sandstone and shale

■ slaty shale

"u" Lilly Unconformity at Red Head

RHS Red Head Syncline

KHS Knobby Hill Syncline

**Figure 18.** *Geology of the Flat Rock area (after King, 1982).*

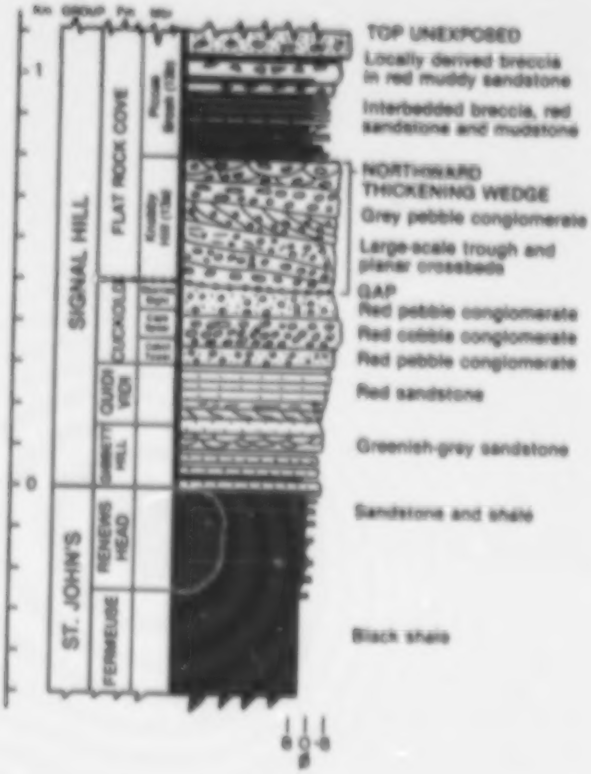

Km
GROUP
Fm.
Mbr
1
0
SIGNAL HILL
ST. JOHN'S
FLAT ROCK COVE
CUCKOLD
QUIDI VIDI
GIBBETT HILL
RENEWS HEAD
FERMEUSE
TOP UNEXPOSED
Locally derived breccia in red muddy sandstone
Interbedded breccia, red sandstone and mudstone
NORTHWARD THICKENING WEDGE
Grey pebble conglomerate
Large-scale trough and planar crossbeds
GAP
Red pebble conglomerate
Red cobble conglomerate
Red pebble conglomerate
Red sandstone
Greenish-grey sandstone
Sandstone and shale
Black shale

**Figure 19.** *Composite stratigraphic section of the Signal Hill Group at Flat Rock Cove.*

**Plate 34.** *Principal reference section of Cape Spear Member, Logy Bay. Cobble conglomerate forms cliff in foreground. (Photograph courtesy of Ben Hansen)*

Within the core of the Blackhead Syncline, red and grey sandstones and mudstones of the Blackhead Formation have an exposed thickness of about 1.7 km. This formation is the highest stratigraphic unit within the St. John's region (Figure 16). The top of the formation is not exposed but may be present below Paleozoic rocks in St. John's Bay as the syncline plunges northward (King, 1988). Sporadic exposures of the lower part of the formation are well exposed between Torbay Point and Petty Harbour where they form the prominent headlands of Redcliff, Sugarloaf Head, Small Point, and Horseshoe Cliff.

The Blackhead Formation probably continues as an offshore belt between Petty Harbour and the Ballard Bank, 16 km east of Cape Race in southeastern Avalon Peninsula. Ballard Bank is a northerly-trending submerged ridge about 19 km long by 1.5 km wide, and consists of arkosic sandstone and argillite that Lilly (1965, 1966) correlated with the Blackhead Formation. The Blackhead Formation may be coeval with the Flat Rock Cove Formation (Figure 6) and with the upper part of the Musgravetown Group but, because of lithological differences in the type sections, no definite correlation may be made.

The Blackhead Formation is here formally subdivided into five new members, which in ascending stratigraphic order are Petty Harbour, Maddox Cove, Spriggs Point, Deadman's Brook and Cliff Point (Figure 16). The Petty Harbour, Spriggs Point and Cliff Point members are mainly red, arkosic sandstones with similar compositional and textural variations. Prominent red mudstones of the Maddox Cove Member separate the Petty Harbour and Spriggs Point members. Green mudstones and shales of the Deadman's Brook Member separate the Spriggs Point and Cliff Point members.

**Plate 35.** *Exotic clast of quartz–sericite schist, Cape Spear Member, Cuckold Formation, Logy Bay. Clast maximum dimension 6 cm.*

### *Petty Harbour Member (Subunit 12a)*

*Name, Distribution and Thickness.* The Petty Harbour Member gradationally overlies the steeply eastward dipping conglomerates of the Cuckold Formation (Figure 15). The type section is along the Petty Harbour–Maddox Cove Road; the lower boundary is 225 m west of the breakwater at the cemetery road junction and the upper boundary at the old Maddox Cove Road bridge. The estimated stratigraphic thickness is about 400 m.

The Petty Harbour Member forms the low sloping, poorly exposed ground east of the Southside Hills and gradually thins northward. It is also exposed at Gunners Cove (Freshwater Bay), Skerries Bight, Sugarloaf Head and Redcliff. The Maddox Cove Member pinches out at Logy Bay and the Petty Harbour Member merges with the Spriggs Point Member.

*Lithology and Contact Relations.* The Petty Harbour Member is a transitional unit between the conglomerates of the Cuckold Formation and the sandstones and mudstones of the Blackhead Formation (Figure 16). Thick bedded, very coarse grained, sandstone and granule conglomerate gradually fine upward into mainly coarse sandstone, which occurs at the top of the unit. Red mudflake breccia, large internal loads, deformed mudflake horizons and oversteepened trough crossbeds are all abundant.

### *Maddox Cove Member (Subunit 12b)*

*Name, Distribution and Thickness.* The Maddox Cove Member is the most distinctive and easily recognizable unit of the Blackhead Formation. Its interbedded red mudstones, siltstones and sandstones (Figure 16) are well exposed in low coastal cliffs and roadcuts in the northern Maddox Cove area (Plate 36). The type section is designated in coastal exposures between the bridge on the old Maddox Cove Road and the southern slope of Three Peak Hill (i.e., 700 m due south of survey monument # 326580, map sheet 1257). The unit is approximately 250 m thick and it appears to maintain this thickness along a narrow valley that extends northward from the cove to Freshwater Bay. Similar facies occur at Skerries Bight and represent a northern continuation of the member.

*Lithology.* Within the Maddox Cove type section, numerous fining and thinning upward megasequences are present and are characterized by various scales, geometries, rock types and combinations of sedimentary structures. Sand to mud ratios, for example, are extremely variable; mud forms between 25 to 75 percent of each cycle and generally about 50 percent. Four principal facies have been recognized:

| | |
|---|---|
| A-12b | very thick-bedded sandstone associated with mudflake breccia |
| B-12b | alternating, thin red sandstone and mudstone |
| C-12b | red mudstone having thin lenses or laminae of siltstone and sandstone |
| D-12b | green, tuffaceous mudstone and siltstone. |

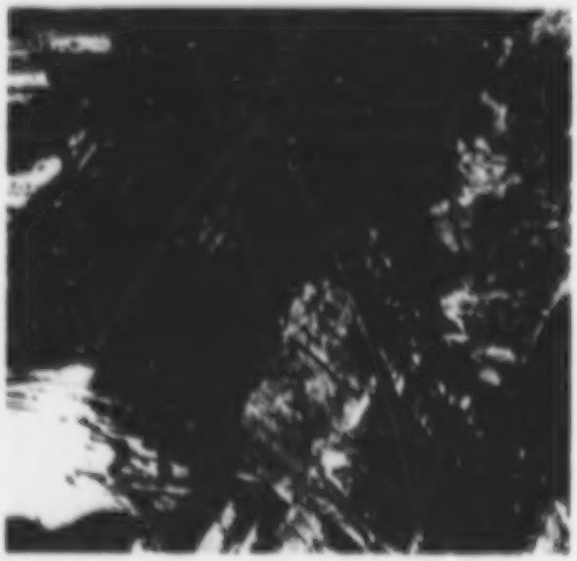


**Plate 36.** *Red mudstone, siltstone and sandstone (facies A, B, C) of the Maddox Cove Member, Maddox Cove.*

Facies A-12b consists mainly of pale red to buff weathering, medium- to coarse-grained arkosic sandstone, which generally occur as very thick (1 to 3 m), tabular or sheet-like bodies with grouped (pi) trough crossbeds throughout. The lower bounding surface of each sandstone unit is erosional and is planar to locally scoop-shaped; rip-up clasts of red mudstone are abundant, particularly near the base. The upper boundary is commonly gradational into facies B-12b.

Facies B-12b usually overlies facies A-12b and typically consists of thick (1 to 2 m) sheet-like units of alternating, red sandstone and mudstone with some thin interbeds of parallel and cross-laminated siltstone. Small-scale cross-bedding and linguoid ripples indicate variable flow conditions. Mudstones show large polygonal dessication cracks infilled with sand. Numerous sandstone dykes and sills are also present (Plate 37), many of which emanate from the underlying facies A-12b.

Facies C-12b in most places gradationally overlies facies B-12b and consists of 0.5- to 5-m-thick tabular units of mainly red mudstone, which have thin lenses of cross-laminated siltstone and sandstone. Very thick units of facies C-12b may also contain intercalations of facies A-12b or B-12b. Many reduced green bands can be seen within the otherwise red mudstone. Although facies C-12b is typically sharply overlain by facies A-12b having a planar contact, it is locally steeply erosive; both facies B-12b and C-12b may terminate laterally against a large scoop-shaped channel, infilled with facies A-12b.

Facies D-12b is associated with facies C-12b and consists of medium units of green tufflaceous mudstone and siltstone associated with abundant volcanic shards; it is recognized by a pale-green colour and with a very siliceous appearance. This facies occurs in the lower part of the unit and was

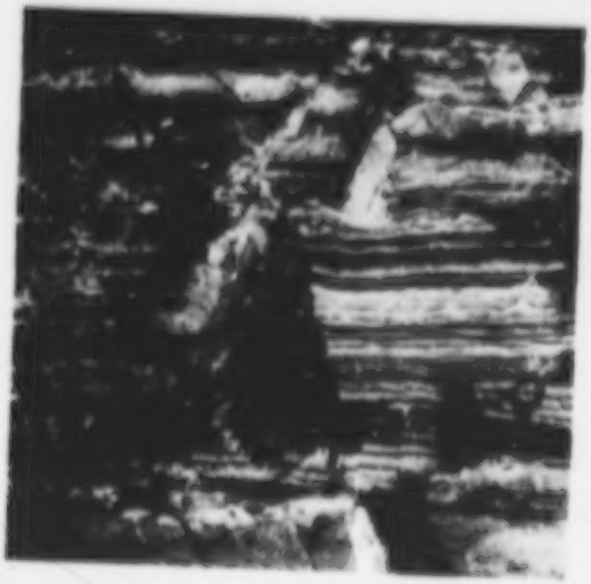


**Plate 37.** *Alternating sandstone and mudstone, cut by sandstone dykes (facies B-12b). Maddox Cove Member, Blackhead Formation.*

temporarily exposed in a roadcut about 400 m north of the Maddox Cove Road bridge. It is similar to tuffaceous interbeds in the Quidi Vidi, Gibbett Hill and Renews Head formations.

*Contact Relations and Correlation.* The Maddox Cove Member conformably overlies the Petty Harbour Member and is conformably overlain by the Spriggs Point Member. The lower and upper boundaries are drawn arbitrarily within zones of interfingering and are respectively placed at the lowest and highest occurrence of facies B-12b and C-12b.

Between Skerries Bight and Robin Hood Bay, the Maddox Cove Member laterally intertongues with the Petty Harbour and Spriggs Point units and pinches out at Logy Bay (Figure 7). Interbeds of red sandstone and mudstone between Herring Cove and Spear Bay, occur on the eastern limb of the Blackhead Syncline; the stratigraphic level of this 200-m-thick unit corresponds with that of the Maddox Cove Member, although facies B-12b and C-12b are poorly developed in Spear Bay.

*Spriggs Point Member (Subunit 12c)*

*Name, Distribution and Thickness.* The Spriggs Point Member is the dominant unit in the Blackhead Formation (Figure 16) and is centred around Spriggs Point, St. John's Bay. It has an estimated thickness of 800 m in the type section designated between Freshwater Bay (100 m east of the barachois) and the western side of Deadman's Bay. The unit forms much of the core of the Blackhead Syncline and is well exposed between Cantwells Cove and Blackhead Brook; its thickness there is approximately 750 m.

*Lithology.* The Spriggs Point Member is divided into a lower (Unit 12cl, Map 90-120) and an upper part (Unit 12cu, Map 90-120) in the type section and in the Blackhead area, but these divisions are difficult to map in the thick forest and marshy ground south of the Cape Spear Road. The lower part (facies A-12c) consists of about 550 to 600 m of medium- to thick-bedded red arkosic sandstone, having thin interbeds of red mudstone and is comparable in lithofacies with the Quidi Vidi Formation and the Petty Harbour Member (Blackhead Formation). The sandstones are medium to very coarse grained and are characterized by large scale, grouped trough crossbeds and abundant rip-up clasts of red mudstone (mudflake breccia). In thin section, the grains are subangular to subrounded and consist of 30 to 35 percent quartz, 10 percent potash feldspar, 20 to 25 percent plagioclase, 15 to 20 percent rock fragments (rhyolite, granite, granophyre), 15 to 20 percent matrix (Plate 38).

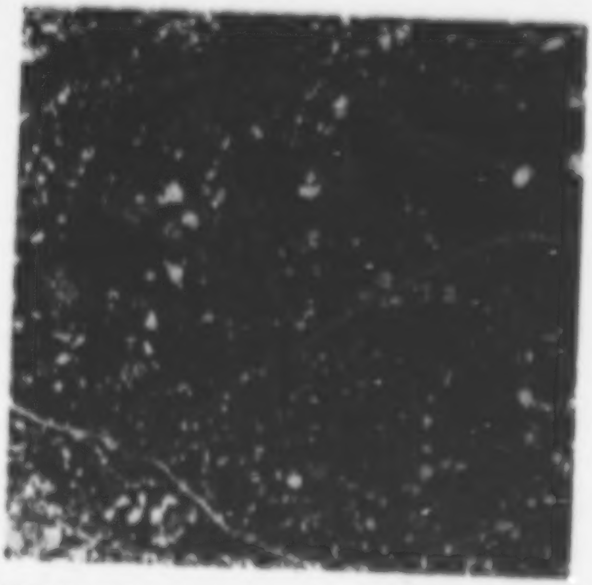


**Plate 38.** *Thin section of medium- to very coarse-grained arkosic sandstone (facies A-12c). Spriggs Point Member. Note local concentrations of rock fragments (rhyolite, granophyre).*

The upper part (facies B-12c) consists of about 200 m of buff to pale red weathering green sandstone, which resembles facies A-9 in the lower part of the Gibbett Hill Formation. Apart from the difference in colour, which may indicate reducing conditions, this lithofacies is comparable with the underlying red beds. Inland exposures, particularly along the axis of the Blackhead Syncline (e.g., east of Crown Hill) are frost heaved and paleocurrent readings on cross-bedding are unreliable. Readings taken in coastal exposures show paleoflow to the southwest.

*Contact Relations and Correlation.* Competent sandstones of the Spriggs Point Member mainly controlled the development of the Blackhead Syncline. The boundary with the underlying Maddox Cove Member is conformable but drawn arbitrarily within a zone of interfingering; the boundary with the overlying Deadman's Brook Member appears to be sharp. A generalized boundary between the lower and upper parts of the Spriggs Point Member (Figure 7) is based solely on colour variations, which may be diagenetic; this boundary is approximately equivalent to the contact between map units 5A/5B of Rose (1952), for the Blackhead Formation. Correlatives of the member form the distinctive promontories of Small Point, Sugarloaf Head and Radcliff Head.

*Deadman's Brook Member (Subunit 12d)*

*Name, Distribution and Thickness.* The Deadman's Brook Member has an estimated thickness of 75 m and is the thinnest within the Blackhead Formation; in general, between 4 and 5 m are exposed at any single locality. The type section is along Deadman's Brook near its mouth at Deadmans Bay. The member continues southward to the old Blackhead Road (survey monument # 026526, map sheet 1254) and thence northeast along the Blackhead Road to Blackhead village. Access to the type section is difficult from the cliff top and is best reached by boat from the village.

*Lithology.* The Deadman's Brook Member consists of dark-green mudstone and thin-interbeds of green sandstone. The sandstones are comparable with the sandstones of the upper part of the Spriggs Point Member and the Gibbett Hill Formation.

*Structural Relations and Mineralization.* The Deadman's Brook Member defines a U-shaped belt in the northward plunging core of the Blackhead Syncline. It is in sharp, conformable contact with the underlying Spriggs Point Member and the overlying Cliff Point Member. The Deadman's Brook Member is highly fractured and is cut by small, normal faults with up to several metres displacement. Some fractures are infilled with veinlets of quartz and bornite–covellite; a whole-rock trace-element XRF analysis is shown in Table 6. Similar copper-bearing veinlets occur elsewhere in the Signal Hill Group (e.g., Shoal Bay, Petty Harbour, White Hills, Quidi Vidi) but their narrowness (1 to 10 mm) and wide spacing preclude economic development.

*Cliff Point Member (Subunit 12e)*

*Name, Distribution and Thickness.* The Cliff Point Member has an exposed thickness of about 275 m and is the highest exposed stratigraphic unit within the Blackhead Formation. Its name is derived from Cliff Point, a 125-m-high cliff halfway between Deadmans Bay and Blackhead Bay. The well-exposed and accessible type section extends from Blackhead wharf, westward along Cliff Point to the highest exposed beds; this section is repeated on the west limb of the Blackhead Syncline between Cliff Point and Deadmans Bay, but access is difficult from the cliff top.

*Lithology.* The Cliff Point Member mainly consists of medium to thick beds of red to buff arkosic sandstone with minor interbeds of red and green mudstone (Figure 16). The facies is comparable with the Quidi Vidi Formation and other coarse red beds within the Blackhead Formation. The sandstones are medium to very coarse grained and are characterized by large scale, grouped trough crossbeds and abundant mudflake breccia. In thin section, the red sandstones consist of subangular to subrounded grains of 25 to 35 percent quartz, 30 to 35 percent potash and plagioclase feldspar, 15 to 25 percent rock fragments (rhyolite, granophyre, granite) and 10 to 20 percent matrix.

**Table 6:** Whole-rock trace-element analysis of the bornite–covellite vein, Deadman's Brook Member, Blackhead Formation

| ELEMENT | PARTS PER MILLION |
|---|---|
| Cu | 161536 |
| Ba | 421 |
| Zn | 256 |
| La | 19 |
| Zr | 18 |
| Nb | 14 |
| Y | 9 |
| Sr | 7 |
| V | 7 |
| Rb | 3 |
| Pb | 1 |
| U | 0 |
| Th | 0 |
| Ga | 0 |
| Ni | 0 |
| Ti | 0 |
| Ce | 0 |
| Cr | 0 |

XRF Analysis of pressed powder pellet by D.H.C. Wilton, Department of Earth Sciences, Memorial University of Newfoundland.

Sample No.: AK 85-1371

*Contact Relations.* The Cliff Point Member forms the core of the Blackhead Syncline. It is in sharp, conformable contact with the underlying Spriggs Point Member. The highest exposed beds of the Cliff Point Member extend below St. John's Bay and are now known to be in close proximity, and possibly overlain, by lower Paleozoic strata (King, 1988).

## Flat Rock Cove Formation (Unit 13)

The Flat Rock Cove Formation lies in the northeast part of the map area (Figure 7). It provides an important stratigraphic link with a once tectonically active basin margin. Its precise stratigraphic position in the Signal Hill Group is uncertain (Figure 6).

### *Name, Distribution and Thickness*

Rose (1952) included rocks of the Flat Rock area in the Blackhead Formation; they were included within the Signal Hill Formation by Gale (1968). King (1982) named the Flat Rock Cove Formation and designated the rocks in the coastal cliffs between Knobby Hill and Red Head, Flat Rock Cove, as the type locality (Figure 18). The formation is a large clastic wedge that pinches out to the south and is therefore a distinctive local facies, rather than an extension of the Blackhead Formation. The formation has an exposed thickness of about 600 m at the type locality, although its original maximum thickness may be in excess of 1000 m. Its distribution is limited to the Flat Rock Cove area.

## *Lithology*

The Flat Rock Cove Formation consists of two lithologically contrasting members, named by King (1982) the Knobby Hill and Piccos Brook members. Thick- to massive-beds of grey conglomerate of the Knobby Hill Member are overlain by red mudstones, sandstones and breccias of the Piccos Brook Member. A composite stratigraphic section is shown in Figure 19.

### *Knobby Hill Member (Subunit 13a)*

*Name, Distribution and Thickness.* The type section of the Knobby Hill Member (King, 1982) is along one kilometre of coastal cliffs south of Knobby Hill to the southwestern corner of Flat Rock Cove (Plate 3). The member has a maximum exposed thickness of 300 m, although it is presumed to be least 500 m at Flat Rock Point (Figure 18).

*Lithology.* The Knobby Hill Member consists of buff weathering, grey, clast and matrix supported conglomerate with interbedded pebbly sandstone and minor siltstone. Very thick to extremely thickly bedded units of conglomerate around Flat Rock Cove appear tabular, but as seen south of Flat Rock Point, they form very extensive stacked wedges, each of which gradually thins out to the south; master bedding planes representing major erosional surfaces define the geometry of the sand bodies. Large-scale solitary and grouped trough crossbeds (Plates 39 and 40) are present within the Knobby Hill Member and show unimodal paleoflow to the south-southwest (Figure 15).

Clast-supported conglomerates are typically well imbricated and in a downflow direction (i.e., to the south) may show a rapid transition into unoriented or poorly imbricated granule conglomerate, through to sand. These changes reflect a decrease in stream competence downfan (i.e., a more distal environment). Minor intercalated units of thin- to medium-bedded sandstone, parallel laminated siltstone, and massive mudstone having sand-filled desiccation cracks also increase downfan (i.e., to the south).

Pebble to cobble size clasts are subangular to rounded, although half-round and angular rip-up clasts of local derivation are abundant. Percussion marks are present on siliceous cobbles and were produced by clasts vigourously bouncing against one another during transport. The clasts are composed of mainly felsic volcanic rocks and siliceous siltstone. White-weathering, jet black and glassy clasts of porphyritic rhyolite are petrologically identical to the sodic rhyolites in the large intrusive domes of Cape St. Francis area; they contain euhedral phenocrysts (1 to 2 mm in diameter) of albite with complex twinning, set in a devitrified matrix.

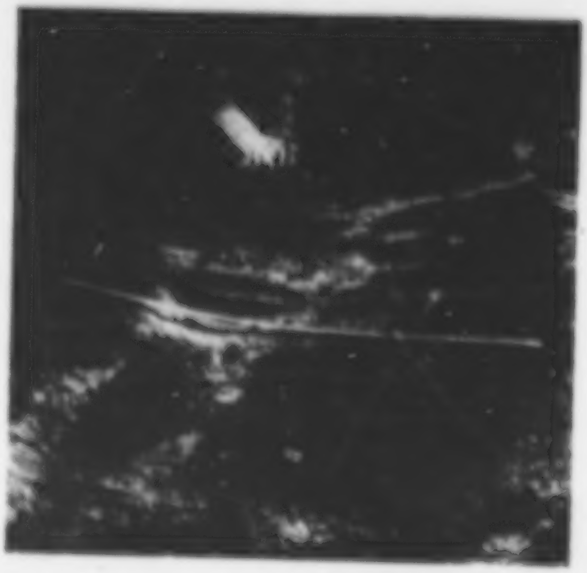


**Plate 39.** *Large-scale trough crossbed in Knobby Hill Member, Flat Rock. Paleoflow to south-southwest.*

**Plate 40.** *Large-scale planar crossbeds within pebble conglomerate of Knobby Hill Member, Flat Rock Point.*

*Structural Relations, Correlation and Age.* Looking northward from Knobby Hill, a broad valley descending toward Flat Rock Cove follows the axis of a north plunging open syncline (Knobby Hill Syncline) in beds of buff to whitish weathering conglomerate (Knobby Hill Member). The conglomerates around the cove have a low dip (15°), hence the origin of the name Flat Rock.

The Knobby Hill Member appears to conformably or disconformably overlie the Skerries Bight Member of the Cuckold Formation at Knobby Hill, but on the coast, it appears to overlie the stratigraphically lower Cabot Tower Member (Figure 18). Because of bedding plane faults, difficult access (120 m sheer cliffs), and poor inland exposures, there is considerable doubt about the nature of the boundary. It may represent:

1. a conformable contact with minor shearing
2. a disconformity, or
3. an early thrust fault with subsequent folding of both fault and associated members.

The Knobby Hill Member is terminated in the west by the Flat Rock Thrust Zone, (Figure 20) and in the north it is interfingered with the lower part of the Piccos Brook Member (Plate 41). There are no correlatives within the map area or elsewhere on the Avalon Peninsula with the possible exception of a grey pebble conglomerate (Bellevue Beach Member, Heart's Content Formation), which occurs in the Trinity–Placentia–St. Mary's Bay region (King, 1988); this member was probably derived in part from the Bull Arm Formation (Musgravetown Group) and in part from the Connecting Point Group.

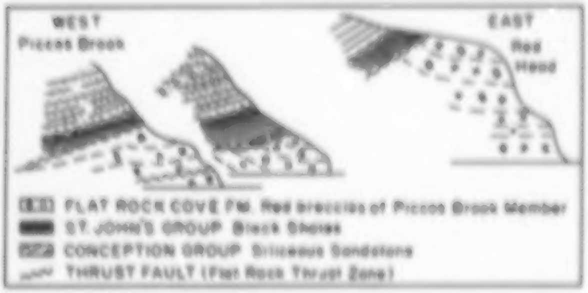

WEST
Piccos Brook
EAST
Red Head
FLAT ROCK COVE FM. Red breccias of Piccos Brook Member
ST. JOHN'S GROUP Black Shales
CONCEPTION GROUP Siliceous Sandstone
THRUST FAULT (Flat Rock Thrust Zone)

**Figure 20.** *Diagrammatic sections across the Flat Rock Thrust Zone, north of Piccos Brook, Flat Rock Cove (modified after Anderson* et al., *1975).*

The age of the Knobby Hill Member is uncertain but as inferred from its stratigraphic position it may be Paleozoic. If the rhyolitic clasts within the member were derived from rhyolitic domes either from or coeval with those of Cape St. Francis area, then the 585 Ma age of those rocks (Krogh *et al.*, 1983, 1988) represents a maximum age of the deposit.

### *Piccos Brook Member (Subunit 13b)*

*Name, Distribution and Thickness.* King (1982) named the member and designated the type section in 2.5-km-long coastal cliffs between the southwest part of Flat Rock Cove, the mouth of Piccos Brook and the north side of Red Head (Figure 18). The unit has a maximum exposed thickness of 300 m.

*Lithology.* The Piccos Brook Member is similar to the Knobby Hill Member, in that it is characterized by an overall coarsening and thickening-upward sequence (Figure 19). It consists of interbedded red sandstone, and both sand matrix- and clast-supported breccia.

**Plate 41.** *Interfingering of Knobby Hill and Piccos Brook members, Flat Rock Cove.*

The lower part of the member to the south of Piccos Brook, is comparatively well-bedded, finer grained, with a higher mud content. It shows alternating thin to thick, parallel-stratified units of red desiccated mudstone, cross-stratified sandstone and breccia. Breccia beds predominate in the upper exposed part of the member between Piccos Brook and Red Head (Figure 21). Megaclasts at Red Head have a maximum long dimension of one metre, but mainly between 10 and 20 cm; they rapidly decrease in abundance and size southward. Flat megaclasts in the breccia are made up almost entirely of poorly sorted, fragmented beds of siliceous siltstone and sandstone derived from the Drook Formation. Minor (one percent or less) granitic clasts indicate unroofing of a pluton to the northeast. The sheet-like, clast-supported breccias rest unconformably above folded strata of the Conception Group at Red Head (Figures 18 and 21); this important structure is known as the Lilly Unconformity (Anderson *et al.*, 1975).

*Structural Relations and Age.* The Piccos Brook Member defines the gently northward plunging Red Head Syncline (Figure 18). It conformably overlies the Knobby Hill Member by interfingering (Plate 41) and the boundary is placed at the lowest red beds. At Red Head, the Lilly Unconformity (Anderson *et al.*, 1975) separates the Piccos Brook unit from folded Drook strata (Figure 21). On the western side of Flat Rock Cove, the Member is terminated by the Flat Rock Thrust Zone. The top of the Piccos Brook Member is not present and its original vertical stratigraphic extent is unknown.

The age of the Piccos Brook Member is uncertain. As one of the youngest stratified units in the map area, it may possibly be Paleozoic.

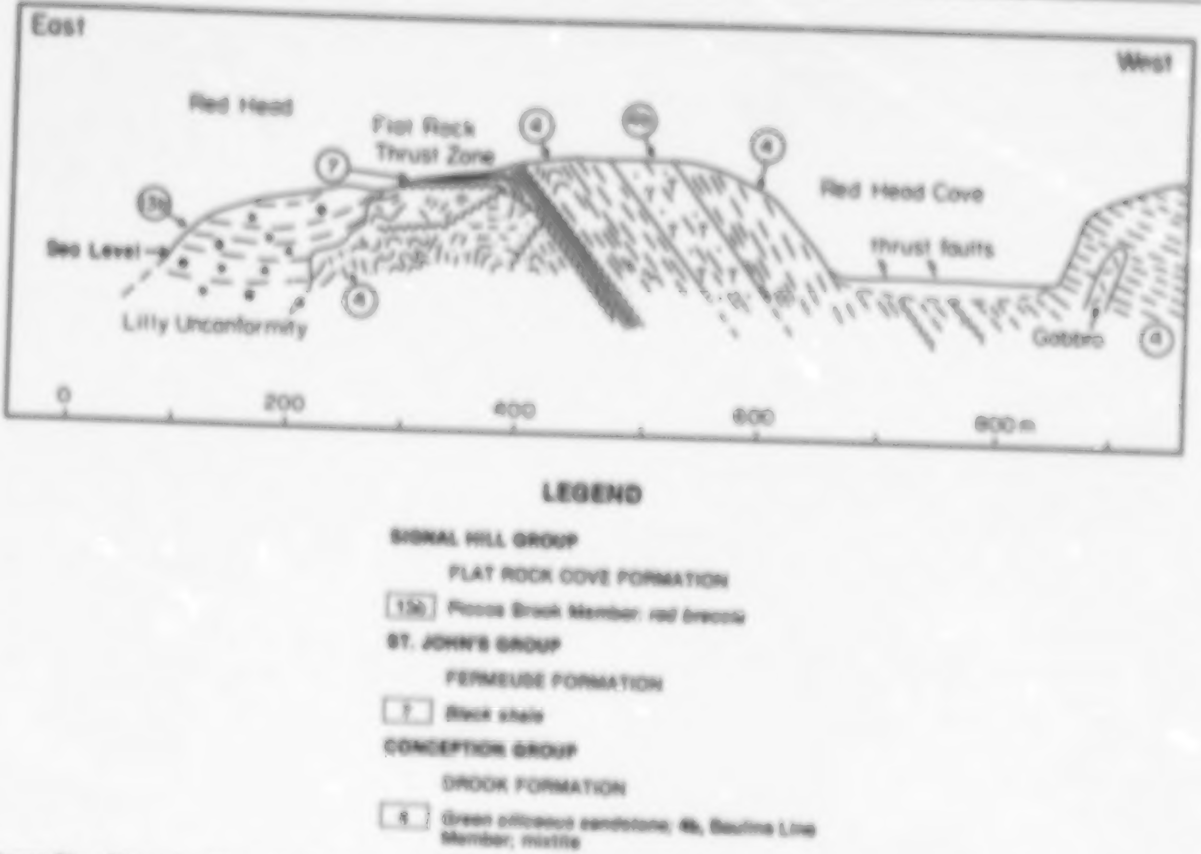

East
West
Red Head
Flat Rock
Thrust Zone
7
4
4b
4
13b
Sea Level
4
Lilly Unconformity
Red Head Cove
thrust faults
Gabbro
4
0
200
400
600
800 m
LEGEND
SIGNAL HILL GROUP
FLAT ROCK COVE FORMATION
13b Piccos Brook Member: red breccia
ST. JOHN'S GROUP
FERMEUSE FORMATION
7 Black shale
CONCEPTION GROUP
DROOK FORMATION
4 Green siliceous sandstone; 4b, Bauline Line Member; mixtite

**Figure 21.** *Diagrammatic cross-section through Red Head area showing the Lilly Unconformity and the Flat Rock Thrust Zone (modified after Anderson* et al., *1975).*

## DOGBERRY HILL GABBRO (UNIT 14)

Weakly to strongly deformed diabase and gabbroic dykes, sills and stocks (e.g., Plate 7) are locally numerous in the western part of the map area (Figure 7); they are presumed to be feeders to Proterozoic and possibly Paleozoic volcanic rocks. The sheared Dogberry Hill Gabbro is a uniform, medium- to coarse-grained rock and is possibly an intrusive equivalent of the massive pyroxene–plagioclase Whalesback Gabbro (Williams and King, 1979) of the southern Avalon Peninsula. A small, gabbro plug about halfway between Stiles and Red Head Cove is presumed to intrude the Mannings Hill Member of the Drook Formation.

Numerous diabase dykes and sills are present between Small Point and Shoe Cove; a prominent 1 to 3 m thick, vertically dipping diabase dyke (azimuth 160° true) intrudes the Mannings Hill Member at Small Point. The undeformed diabase dykes that cut the Drook Formation strata between Shoe Cove and Red Head are lithologically comparable with those in the Bonavista Peninsula region, and may possibly be of the same age.

## HOLYROOD INTRUSIVE SUITE (UNIT 15)

The Holyrood Intrusive Suite occurs immediately to the southwest of the map area (Figures 3 and 7) and consists of mainly granite and granodiorite, associated with minor amounts of quartz monzonite and gabbro. Aplite dykes and small bodies of pegmatite and granophyre are present near the margins and indicate high-level intrusion (Hughes, 1971). Clasts, similar in composition to the Holyrood Intrusive Suite, occur within the Signal Hill Group. Minor granitic detritus throughout the Conception Group is evidence of older granitoid bodies. Granitoid rocks are known to be present also in the offshore (e.g., Pelletier, 1971).

Weakly to strongly deformed felsic intrusive rocks are present in the western part of the map area and may be genetically related to the Holyrood Intrusive Suite. Thin (0.2 to 1 m) boudins and sheared sill-like intrusions of coarse-grained to pegmatitic granite occur in the highly sheared St. Phillips and Portugal Cove formations. Pegmatitic granite occurs along the Freshwater Pond Fault Zone (e.g., 250 m south of Northwest Pond). Rhyolitic domes, dykes and sills also occur within the western part of the map area where they intrude the Portugal Cove and St. Phillips formations.

# PALEOGEOGRAPHIC EVOLUTION

## MAJOR PRECAMBRIAN FACIES AND FORMATIONS

Schematic diagrams of the proposed paleogeographic evolution of the Avalon Peninsula, shown in Figure 22, are based on regional studies by King (1980, 1982, 1984) and are applicable to the Precambrian rock units in the map area. They reflect a long history of volcanic activity, marine and terrestrial sedimentation, uplift and subsidence.

### Submarine Mafic Volcanism

#### *The Harbour Main Group*

The basaltic pillow lava and massive mafic flows *(Princes Lookout Formation)*, tuffs *(St. Phillips Formation)* and associated volcaniclastic rocks *(Portugal Cove Formation)* of the Harbour Main Group, represent an early history of submarine volcanism and marine sedimentation. As shown in Table 3, the mafic flows appear to be chemically similar to average hawaiite (MacDonald and Katsura, 1964) and to basic lavas present in the Harbour Main volcanic belt west of Colliers (Papezik, 1970). A discriminant diagram of *Zr*/Y ratio against *Zr* (Figure 8) suggests that they are suprasubduction zone basalts, probably early island-arc tholeiites (IAT), which formed in a marginal ocean basin (Figure 22). Basalts from back-arc basins commonly have a geochemical signature between mid-ocean ridge basalts (MORB) and island-arc tholeiites (Saunders and Tarney, 1984). The limited number of trace-element analyses precludes pinpointing a specific near-arc site.

Tuffite-rich 'proximal' turbidites of the Portugal Cove Formation probably represent a transition into the cherts and turbiditic sandstones of the Broad Cove River Member (Drook Formation). The presence of rip-up clasts of tuff and mafic lava fragments in the lowermost beds of the Broad Cove River Member suggests that this unit may overlie or interfinger with mafic volcanic rocks of the Harbour Main Group. As shown in Figure 22, the Harbour Main Group and the lower part of the Conception Group in the St. John's area are largely penecontemporaneous. The Broad Cove River Member and the St. Phillips and Portugal Cove formations are intruded by gabbroic to diabasic rocks, which may be feeders to submarine mafic flows.

### Submarine Felsic Pyroclastic Activity and Basinal Sedimentation

#### *The Conception Group*

The next major stage, in the Late Precambrian evolution of the area, was dominated by a long period of widespread submarine pyroclastic activity and marine turbiditic and pelagic sedimentation. Although basement rocks are unexposed in the Avalon Zone of Newfoundland, they are present in other parts of the zone (e.g., Nova Scotia and New Brunswick); it is therefore assumed that continental type rocks were present, subsequently melted and gave rise to the felsic volcanic rocks and tuffs. Minor felsic dykes ('soda' rhyolites) intrude the Harbour Main Group, and between Brocks and Hickeys ponds and continuing northward toward Cape St. Francis, abundant felsic flows, dykes, sills and domes are also present (e.g., subunit 3a) and probably formed part of the source area for the pyroclastic and epiclastic detritus in the Conception and Signal Hill groups.

A variety of tuffs in the Conception Group are intermixed with minor granitic and other nonvolcanic debris. Tephra present in the Conception Group may have originated from subaerial volcanoes, by subaqueous eruptions, or by both. Pelagic fallout, pyroclastic flows, slumping, turbidity currents, mass flows and contour currents are all major processes, which are interpreted to have occurred within the marine basin during felsic explosive activity and in long quiescent periods following effusive activity.

The greenish-grey cherts of the *Broad Cove River Member* probably formed by intense silicification of very fine-grained volcanic detritus; the Harbour Main Group lavas and pyroclastics were the likely sources of silica. The abundance of tuff and other volcanic detritus throughout the unit, suggests marine sedimentation contemporaneous with volcanism. Coarse-grained turbiditic sandstones, interbedded with the cherts, are interpreted as suprafan lobe facies (Figure 23) deposited by progradation of a submarine fan from a volcanic source terrane.

The lower part of the Conception Group is also well exposed in coastal outcrops of eastern St. Mary's Bay. Deep-water siliceous turbidites of the *Mall Bay Formation* are overlain by glaciogenic debris flows of the *Gaskiers Formation* and then by renewed turbidite deposition in the lower part of the *Drook Formation*. A schematic depositional model, proposed by Gardiner (1984) for the lower Conception Group (Figure 24) of the southern Avalon Peninsula, is applicable to equivalent strata in the map area.

The epiclastic mixtite facies of the Bauline Line Member (Drook Formation), characterized by disorganized conglomerate and coarse-grained to pebbly sandstone (Plates 15, 16 and 17), may represent nested submarine fan–channel deposits (Figure 23). The pebbly sandstones are interpreted as subaqueous debris flows with the coarser deposits probably restricted to submarine fan channels (e.g., Walker, 1979). Downslope movement of clasts was facilitated by a water-saturated mixture of sand and mud. Subrounded cobbles of rhyolite and chert clearly indicate transport of some considerable distance although they may have had a previous history of deposition and attrition before being remobilized. Although comparable facies and processes have been described for the Gaskiers Formation, a glaciogenic component has not been recognized in the Bauline Line Member.

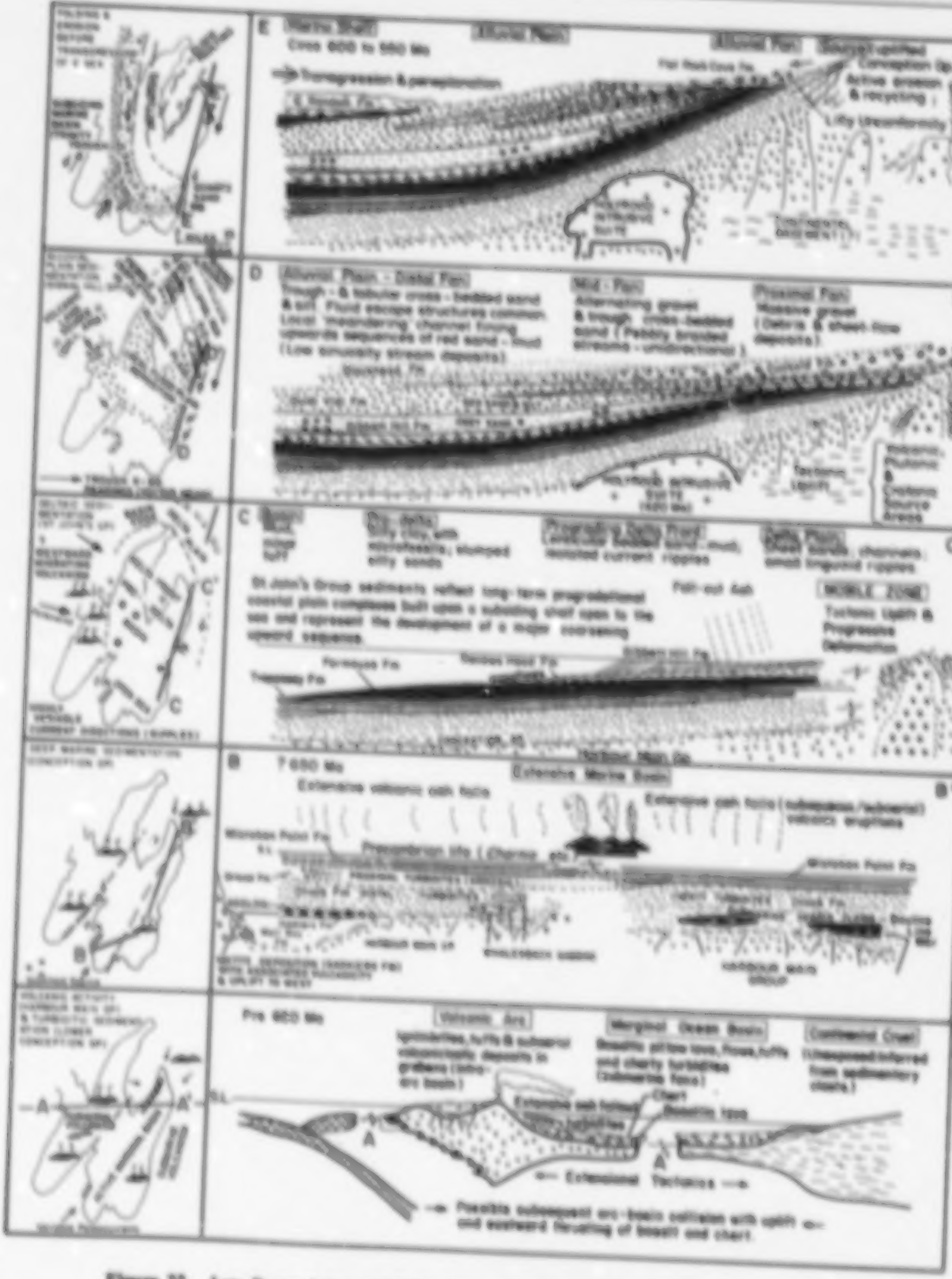

E
Alluvial Plain
Alluvial Fan
Transgression & peneplanation
Active erosion & recycling
Unconformity
E'
D
Alluvial Plain - Distal Fan
Trough - & tabular cross - bedded sand & silt. Fluid escape structures common. Local 'meandering' channel fining upwards sequences of red sand - mud (Low sinuosity stream deposits)
Mid - Fan
Alternating gravel & trough cross-bedded sand (Pebbly braided streams - unidirectional)
Proximal Fan
Massive gravel (Debris & sheet-flow deposits)
D'
Tectonic Uplift
Volcanic, Plutonic & Orogenic Source Areas
C
C'
St John's Group sediments reflect long-term progradational coastal plain complexes built upon a subsiding shelf open to the sea and represent the development of a major coarsening upward sequence.
Fall-out Ash
MOBILE ZONE
Tectonic Uplift & Progressive Deformation
Trepassey Fm
Fermeuse Fm
Renews Head Fm
B
? 650 Ma
Extensive Marine Basin
Extensive volcanic ash falls
Extensive ash falls (subaqueous / subaerial) volcanic eruptions
Mistaken Point Fm
Precambrian life (Charnia etc.)
Mistaken Point Fm
B'
Pre 600 Ma
Volcanic Arc
Marginal Ocean Basin
Continental Crust
Basaltic lava
Chert
A
A'
Extensional Tectonics
Possible subsequent arc-basin collision with uplift and eastward thrusting of basalt and chert.

Figure 23. *Late Precambrian and Early Paleozoic development, eastern Avalon Peninsula.*

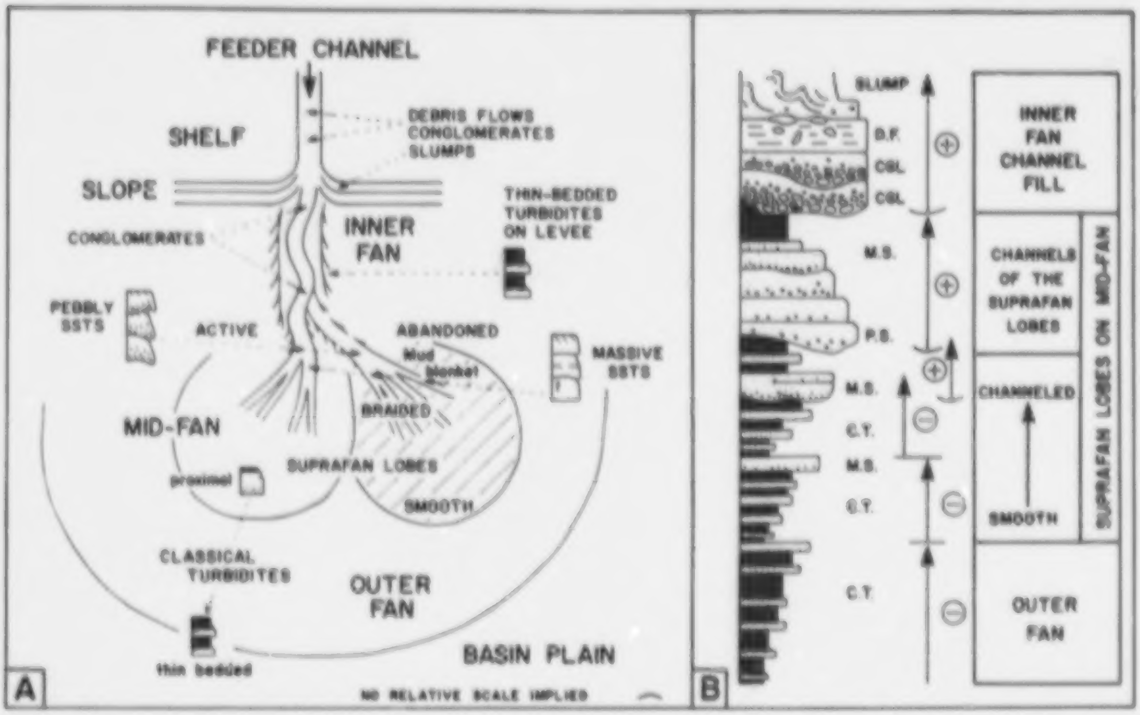

FEEDER CHANNEL
SHELF
SLOPE
DEBRIS FLOWS
CONGLOMERATES
SLUMPS
THIN-BEDDED
TURBIDITES
ON LEVEE
CONGLOMERATES
INNER
FAN
PEBBLY
SSTS
ACTIVE
ABANDONED
Mud
blanket
MASSIVE
SSTS
BRAIDED
MID-FAN
proximal
SUPRAFAN LOBES
SMOOTH
CLASSICAL
TURBIDITES
OUTER
FAN
BASIN PLAIN
thin bedded
A
NO RELATIVE SCALE IMPLIED
B
SLUMP
D.F.
CGL
CGL
M.S.
P.S.
M.S.
C.T.
M.S.
C.T.
C.T.
⊕
⊕
⊕
⊖
⊖
⊖
INNER
FAN
CHANNEL
FILL
CHANNELS
OF THE
SUPRAFAN
LOBES
CHANNELED
SMOOTH
SUPRAFAN LOBES ON MID-FAN
OUTER
FAN

**Figure 23.** *Submarine fan facies models. A. Original fan model proposed by Walker (1979). B. Generalized hypothetical sequence produced during over-all fan progradation. CT = classical turbidites; MS = massive sandstones; PS = pebbly sandstones; CGL = conglomerate; DF = debris flow; SL = slump. Sequences shown by arrows are THIN.-UP (thinning upward) or THICK.-UP (thickening upward) (Walker, 1979).*

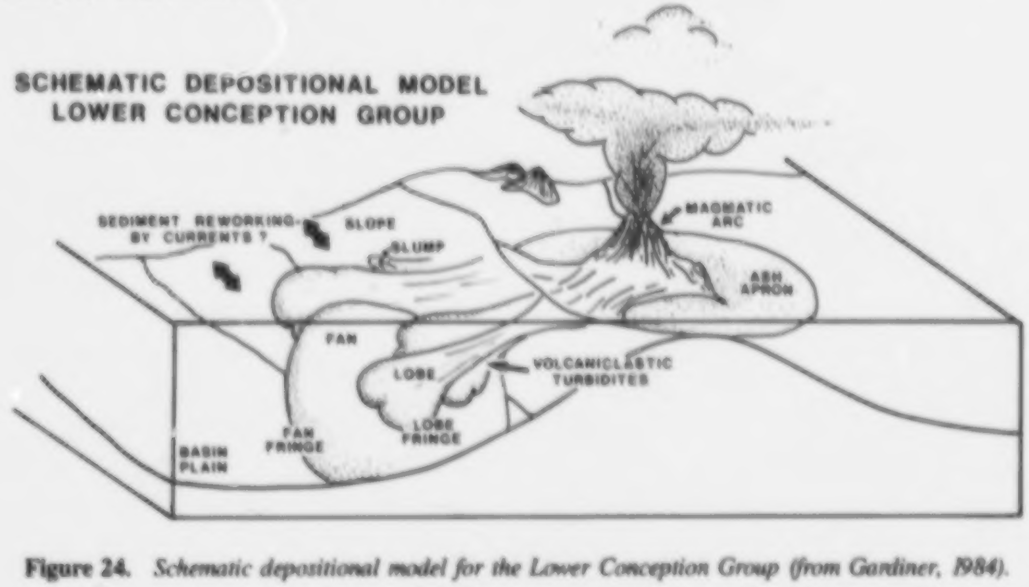

SCHEMATIC DEPOSITIONAL MODEL
LOWER CONCEPTION GROUP
SEDIMENT REWORKING
BY CURRENTS ?
SLOPE
SLUMP
MAGMATIC
ARC
ASH
APRON
FAN
LOBE
VOLCANICLASTIC
TURBIDITES
LOBE
FRINGE
FAN
FRINGE
BASIN
PLAIN

**Figure 24.** *Schematic depositional model for the Lower Conception Group (from Gardiner, 1984).*

Streaky-laminated sandstone (facies B-4c) of the *Torbay Member* (Drook Formation), are here interpreted as slope deposits or contourites. The 'streaky' aspect (Plate 18) is due to a combination of processes involving: 1) movement of thin sand sheets of coarser grains by traction shear; 2) migration of small-scale starved current ripples resulting in lenticular sand laminations; and 3) settling out of pelagic materials (e.g., silt, mud, volcanic ash, shards). Some highly siliceous lenses may have formed by post-depositional compaction and alteration of felsic pyroclastic lapilli causing flattening of pumice and vitric shards. Silicification is widespread throughout the facies. In the northern part of the map area, facies A-4c and B-4c of the Torbay Member occur as interbeds in the mixtites of the Bauline Line Member. This association suggests that they may be submarine slope or overbank deposits associated with materials, reworked by contour currents (Figure 24). The lower facies (A-4c) may also be a 'distal' equivalent of the mixtites with fallout and reworking of fine detritus from turbidity currents. Coarse arkosic sandstones present in the Torbay Dome (e.g., Quarry Road, Torbay) show large-scale pinch-outs, possibly representing margins of broad feeder channels. The upper facies (C-4c) of the Torbay Member is interpreted as a marine, coarse sheet-sand formed by bottom traction currents (contourites); reworking of arkosic sediment caused attrition of feldspars and produced well-sorted quartz sand. The uneven laminae are due in part to shallow scours; lenticular laminae represent sand starved lenses formed by migrating linguoid ripples. Pelagic settling of mud, silt and volcanic ash produced thin irregular drapes of red mudstone containing traces of elongate to Y-shaped bubblewall shards. However, some laminae show very low angle foresets, interpreted as grain-carpet inertia flow produced by rapid fallout with shear.

The *Mannings Hill Member* (Drook Formation) is generally comparable in lithofacies with the Broad Cove River Member. Some scour and broad channel-like features occur, but lateral bed continuity is great (Plate 20). Sedimentary features include rip-up clasts or pebbles along the basal surface, convolute and ripple laminations, normal grading, and sole marks. These medium- to thick-bedded sandstones were primarily deposited by southward-flowing turbidity currents, probably on a mid- to outer-fan environment. The presence of thin interbeds of tuffs and cryptocrystalline chert of volcanogenic origin indicate active volcanism during sedimentation.

The volcanogenic *Mistaken Point Formation*, particularly the Middle Cove Member, represents a period of explosive volcanic activity associated with turbiditic sedimentation. The beds of the *Middle Cove Member* clearly indicate a combination of processes responsible for their origin. Turbidity currents transported much of the coarser volcanic detritus into a shelf or basin that at the same time was receiving considerable influx of acidic pyroclastic material (Plate 21). Medium to thick bedded, fine-grained tuffs with a composition close to that of alkaline rhyolite (Hughes, 1976) may have formed by fallout into water from subaerial volcanoes or may have originated by fallout from underwater eruptions. Thick bedded units of lithic tuff are interpreted as subaqueous pyroclastic (ash) flow deposits (Figure 13). Crude sub-parallel orientation of clasts within the lithic tuffs suggests an initially dense semi-fluidized mass, which flowed rapidly with essentially laminar motion, analogous to a flow-banded rhyolite; mechanisms of this type have been advocated by a number of workers (e.g., Sparks, 1976; Sparks *et al.*, 1980). The presence of granophyre fragments and clasts showing micrographic intergrowth may indicate proximity to ring-dykes concomitant with eruption and caldera collapse. Whether hot pyroclastic flows entered the water from the land or accumulated as a slurry around an underwater vent (e.g., Fiske and Matsuda, 1964; Hughes, 1976) is uncertain. Waterlain tuffs (probably from tephra fallout), subaqueous pyroclastic flow deposits (Fisher and Schmincke, 1984) and associated turbidites were subsequently reworked by marine sedimentary processes. Tuffaceous marker-beds and associated metazoan fossils at the top of the Middle Cove Member define an important chronostratigraphic as well as a biostratigraphic zone.

Sedimentary textures and structures within the overlying *Hibbs Cove Member* indicate deposition by low-density turbulent flows in a large basin plain transitional with an outer fan fringe and slope. Individual flow units having graded tops are observed but frequently difficult to determine due to uniformity in grain size and the presence of diffuse parallel laminations. Parallel-laminated tuffaceous siltstones and mudstones intercalated with the medium bedded argillaceous sandstones probably represent pelagic and hemipelagic detritus reworked by traction flow processes.

## Shallowing Upward Basinal–Deltaic Sedimentation

### *St. John's Group*

The Conception Group is conformably overlain by up to 2 km of marine shale and interbedded sandstone of the St. John's Group, which are a fluvial-dominated deltaic sequence (King, 1980) that progrades and thickens southward (Figures 6 and 22). Greenish-grey tuffaceous siltstone and medium to thin argillaceous sandstone of the *Trepassey Formation* represent a transitional zone into the underlying Mistaken Point Formation with its distinctive metazoan fauna. These fine sands, silts and muds were primarily deposited by 'distal' turbidity currents in a basinal shelf or plain; they reflect high-concentration gravity and traction flow processes and are interpreted as deposits of a turbidite-fronted delta. Pelagic and hemipelagic detritus, including microplankton and volcanic ash were deposited above the sands and were reworked by bottom traction currents.

Overlying black shales of the *Fermeuse Formation* exhibit slumped and resedimented features caused by gravity slumping and sliding (Plate 22); they are interpreted as submarine slope deposits, which were fed by a delta front as it prograded southwards over the shelf. The lower facies (A-7) represents traction-flow processes, giving away to a pelagic settling (Hsu and Jenkyns, 1974) of mud and volcanic ash, probably in a basin plain. The middle facies (B-7) was clearly formed by sediment instability resulting in gravity slumping and disruption of strata on an ancient slope of some considerable magnitude. Considering the widespread distribution of this facies throughout the Avalon Peninsula, the submarine depositional basin probably exceeded 10,000 km$^2$. Similar features on continental slopes have been well documented by a number of workers (e.g., Kelling and Stanley, 1976; Sangree *et al.*, 1976; Nardin *et al.*, 1979). Starved current ripples in the upper facies (C-7) indicate weak bottom traction flow processes.

As shown in Figure 22, the marine basin subsided as it was infilled with sediment, while uplift was taking place beyond its northern margin. The Fermeuse, Renews Head, Gibbett Hill and Quidi Vidi formations are in part diachronous or coeval and formed by lateral accretion and progradation of onshore to offshore facies.

The upper unit of the St. John's Group, the *Renews Head Formation*, represents a shoaling upward of the marine basin. Thin, lenticular-bedded (Plates 24 and 25), rusty-brown weathering sandstone having dark shale laminae (facies A-8), pass upward into thin irregular beds showing ripple-drift cross-lamination, indicating a greater influx of silt and fine sand with traction flow processes becoming increasingly important. Thin-graded beds having sharp bases suggest some transport by turbidity currents. Large varieties of the problematical markings *Aspidella terranovica*, Billings, 1872, present within the shales may represent medusa impressions (Plate 23). Small-scale asymmetrical, straight crested, linguoid and interference ripple marks and flaser bedding (facies B-8) were caused by reworking of the upper part of the sand beds by waves, currents and tides, probably in an inactive distributary-mouth bar environment (e.g., Miall, 1976). Rare gutter casts, flaser-bedding (in which mud lenses were deposited in ripple troughs) and dessication cracks occur near the top of the Renews Head Formation, and may also have formed on a delta top environment modified by storm(?) waves or currents. Major trough cross-stratified channelized sandstones (Facies C-8), intercalated with the shales (Plates 26 and 27), are interpreted as major frontal or distal distributaries, sheet sands and channelized sand lobes of the Gibbett Hill Formation, which generally prograded southward into a shallow marine environment; their stratigraphic position varies throughout the Renews Head Formation, strongly suggesting diachronous relationships. Multidirectional current flow by dunes gave rise to small to medium-scale trough crossbeds. Primary current lineations in some sands indicate rapid flow at times probably in the high flow regime. Rapid deposition of sand above muds resulted in convolute bedding and internal loading. Local tuff beds in the Trepassey and Renews Head formations record intermittent but waning volcanic activity.

## Fluvial Sedimentation

### *The Signal Hill Group*

The channelized southward prograding deltaic sands of the *Gibbett Hill Formation* represent a transition from shallow marine (e.g., Renews Head Formation) to subaerial alluvial plain sedimentation (e.g., Quidi Vidi Formation). Thick to thin irregular sheets of laminated sand (Plate 29) having primary current lineation are interpreted as the product of flash floods, depositing sand under upper-flow regime plane bed conditions (Miall, 1977, 1985; Rust, 1978a, b). Large- and small-scale tabular and trough crossbeds indicate paleoflow to the south and southwest. Numerous small cyclic sequences (sandstone–siltstone–shale) occur throughout the formation with shale units decreasing in thickness and frequency upwards and with sandstone dominant at the top. Localized red beds with mudcracks, major channels and sheet sands at the top of the formation show the development of a subaerial paleoenvironment, probably as a southward prograding lower delta plain within the realm of river-marine interaction (e.g., Coleman and Prior, 1982).

The Gibbett Hill Formation also contains small amounts of detrital muscovite (Singh, 1969) and garnet (Papezik, 1972), possibly derived from a Precambrian gneissic and granitic basement (Papezik, 1972). Tuff beds in the Gibbett Hill and overlying formations of the Signal Hill Group record intermittent deposition of volcanic ash. The presence of tuff and ash beds in the Signal Hill Group indicates contemporaneous sporadic volcanic activity, possibly originating in the Bull Arm region of western Avalon Peninsula.

It is noteworthy that mafic and felsic volcanic rocks that formed mainly in a subaerial environment between ca. 650 and 570 Ma, extend from the Bull Arm region throughout the entire eastern margin of the Appalachians. This period was a time of Precambrian Avalonian movements. In eastern Newfoundland, a rising mountain front on the northern periphery of the present Avalon Peninsula gave rise to alluvial plain conditions, now represented by red sandstones (Quidi Vidi Formation), conglomerates (Cuckold Formation), and variegated sandstones and mudstones (Blackhead Formation), all of which are a molasse-like sequence resulting from a tectonic upheaval (Figures 16 and 22).

Facies within the *Quidi Vidi Formation* are characteristic of an alluvial floodplain environment having dunes fields occupying the deeper parts of broad, active channels. Thick bedded units with primary current lineation and unidirectional cross-bedding were probably generated under flash flood conditions with rapid flow (e.g., Miall, 1965). Paleocurrent studies of solitary and grouped trough crossbeds within the arkosic sandstones indicate south to southwestward flowing streams. An abundance of red mudflakes in the sandstones and extensive scours preserved in thick underlying mudstones attest to the streams erosive nature. As flooding waned, gradual deposition of silt and mud took place in floodplains or in shallow, intermittent playa lakes. Thin sandstones interbedded within thick red mudstone units may represent crevasse splays. Red mudstones locally passing into green mudstones indicate reducing conditions in some areas. During dewatering, mudcracks developed; local fluidized flows of mudflakes and sand were injected as dykes and sills. Abundant large-scale load structures within the thick sandstones are evidence that the sands were liquefied and behaved as quicksands (Plate 31); some mud layers in the fluidized sand were deformed, disrupted and brecciated as a result of liquefied flow.

Facies developed in the *Cuckold Formation* are characteristic of braided river deposits. Large-scale trough and planar–tabular crossbeds indicate unidirectional, high energy traction currents with paleoflow to the south-southwest (Figure 15); these macroforms are consistent with a braided stream environment (e.g., Williams and Rust, 1969; Bull, 1972; Miall, 1977, 1985; Rust, 1978b; Cant and Walker, 1978).

The decrease in pebble size, the relatively high silt and mud content, and the presence of thixotropic deformation structures also support a more distal alluvial plain environment to the south. In general, pebble isopleths and facies in the Cuckold Formation at Cape Spear match with those of Logy Bay; North Head (Motion Bay) facies match with North Head (Narrows). These relationships also indicate generally southwestward paleoflow. The Cuckold conglomerates and sandstones accumulated on an alluvial plain or on the slopes of a major alluvial fan, which built out into an extensive alluvial basin. The wide variety of structures and textures clearly shows that more than one agent of sedimentary process operated here in the distant past. The overall coarsening- and thickening-upward sequences represented by the *Cabot Tower* and *Cape Spear members* (Plates 32, 33 and 34) of the Cuckold Formation reflect a tectonically active basin margin to the north; maximum uplift may have occurred during this period (Figure 22). Pebbles in the Cuckold Formation are predominantly rhyolitic associated with minor granite and granophyre; exotic clasts of quartz sericite schist occur within the Cape Spear Member (Plate 35) and may have been derived from uplifted continental basement rocks.

The average diameter of clasts in the Cabot Tower Member has a gradual southward decline from very large pebble conglomerate at Torbay Point to granule conglomerate at Petty Harbour First Pond (Figure 15). The fluvial environment was dominated by unidirectional traction currents. Trough cross-bedded gravels represent channel fills; planar cross-bedded gravels represent micro-deltaic bedforms probably derived from older linguoid bar remnants.

The upper unit of the Cuckold Formation, the *Skerries Bight Member*, shows gradual fining- and thinning-upward sequences and represents a transitional zone into the sandstones and mudstones of the Blackhead Formation; these vertical changes are interpreted as evidence of a northward retreating source with the various units of the Blackhead Formation also retreating to the north above the coarse gravels of the Cuckold (Figure 22). The Skerries Bight Member formed in a dynamic fluvial environment dominated by unidirectional, southwestward flowing traction currents. For example, the cross-stratified sandy conglomerate with its distinctive grouped (pi) trough crossbeds, probably formed in the deeper part of a very broad, active channel, where the bedload was predominantly sand. Variations in climate, subsidence rates, sediment supply, distance from source and discharge (particularly due to flash floods) may reflect lateral and vertical variations in the member.

Facies within the *Petty Harbour, Maddox Cove, Spriggs Point, Deadman's Brook* and *Cliff Point members (Blackhead Formation)* indicate a braided-stream environment with a paleoflow to the south and southwest. Abundant mudstones and mudflake breccias are characteristic of the Blackhead Formation and probably had developed in playa or intermittent lakes. Large internal loads, deformed mudflake horizon, and oversteepened trough crossbeds are also common throughout the Blackhead Formation; these textures reflect liquefaction produced by ancient groundwaters migrating laterally and upwards on a more distal part of the alluvial plain environment.

Four main facies are recognizable in the *Maddox Cove Member* (Plate 36). Facies A-12b consists of thick, trough-crossbedded, sheet-like sandstones, which are interpreted as the fills of broad ephemeral channels on an arid flood or braidplain. Paleoflow appears to be unidirectional (to the south) but the fluidized (i.e., quicksand) nature of the deposit prior to consolidation may have caused lateral flowage as well as internal loading. Some sands show parallel lamination associated with superimposed primary current lineations, indicative of rapid to upper flow regime conditions at times. Facies B-12b, consists of alternating units of thin, sheet-like sandstones, mudstones and siltstones which are cut by sandstone dykes (Plate 37). This facies is interpreted as having formed in a very shallow floodplain, intermittent playa lake or overbank environment by vertical aggradation or accretion. Subsidence as well as main channel patterns and sediment supply influenced its development. Cant and Walker (1978) showed that in contrast to the lateral accretion within the main channel of a meandering stream, overbank deposition may give rise to vertical accretion deposits in braided streams. Using the South Saskatchewan River sandflats as a model, they noted that near the main river channel, the vertical accretion deposits tend to be silty and commonly cross-laminated, whereas some distance away only mud is deposited; after retreat of the flood, mud and silt dry out and dessication cracks are formed. Facies C-12b consists of red mudstone having thin lenses of cross-laminated siltstone and sandstone; this facies is interpreted as a flood-plain or playa lake deposit. Starved current ripples may have originated as crevasse splays and were reworked by weak currents. Tuffaceous beds are diagnostic of Facies D-12b and indicate active volcanism within the region.

The *Spriggs Point Member* was formed by a sand-dominated river system with southwestward migrating large-scale dunes. Erosion of a rhyolitic and granitic terrane is indicated by the composition of both matrix and rock fragments (Plate 38). Thin mudstones with dessication cracks formed mainly by vertical accretion, although possible point bar sands and muds (e.g., in steep cliffs at Spriggs Point and Blackhead), may represent lateral accretion deposits of meandering or sinuous rivers.

Facies in the *Cliff Point Member*, the highest exposed stratigraphic unit within the Blackhead Formation, are comparable with those of the Quidi Vidi Formation and other coarse red beds within the Blackhead Formation. Trough crossbeds indicate paleoflow to the south and southwest.

The *Flat Rock Cove Formation* is a large southward pinching-out clastic wedge (Figures 18 and 19) that is interpreted as a small, localized, alluvial fan deposit. Clast and matrix supported conglomerates and interbedded pebbly sandstones of the *Knobby Hill Member* represent the products of gravelly, southward flowing braided streams. Trough crossbeds within the conglomerates (Plate 39) are interpreted as the products of gravelly braided streams on the middle to distal part of a small alluvial fan (e.g., Bull, 1972). Clasts of black rhyolite compare with the rhyolite, which forms the domes of Cape St. Francis. Planar crossbeds within the pebbly sandstones (Plate 40) are interpreted as linear to sinuous-crested transverse bars, which moved perpendicular or at high angles to the flow direction on the middle to distal part of an alluvial fan (e.g., Miall, 1985).

Overlying sandstones, mudstones and breccias of the *Piccos Brook Member* are characterized by an overall coarsening- and thickening-upward sequence. Thin to thick units of red dessicated mudstone, cross-stratified sandstone and breccia are characteristic of the lower part of the member. These deposits developed on the lower slopes of the fan; the sands and gravels were probably deposited by sheetfloods during waning floodwater stages. Thick interbeds of conglomerate (Knobby Hill Member) in the lower 30 m of the member represent the interfingering (Plate 41) of two contrasting environments, each with quite different lithofacies assemblages reflecting different source areas (i.e., Harbour Main and Conception groups). Coarse breccia beds in the upper part of the member are composite in origin and are interpreted as debris-flow deposits intermixed with stream and sheetflood deposits in a proximal fan area. Clasts in the breccias are predominantly of Drook Formation lithologies; minor granitic clasts indicate unroofing of a pluton to the northeast. In north-facing cliffs, about 400 m west of Red Head, the Piccos Brook Member near the cliff base rests unconformably above folded strata of the Conception Group; the Lilly Unconformity (Anderson *et al.*, 1975) relates to the Avalonian Orogeny and provides evidence of a major Late Precambrian disturbance. Subsequent deformation (Acadian?) produced the Red Head Syncline.

Variations in climate, subsidence and uplift rates, sediment supply, sediment source areas, distance from source, and discharge, are all factors which influenced lateral and vertical variations in the Signal Hill Group. Rock fragments and constituent detrital minerals indicate that the Signal Hill Group was derived largely from a source area underlain by rocks of the Harbour Main and Conception groups and the Holyrood Intrusive Suite. However, the Gibbett Hill Formation also contains small amounts of detrital garnet and muscovite (Papezik, 1973); this, together with exotic clasts in the Cape Spear Member (Plate 35) and a northeasterly provenance of the Signal Hill Group sediments, may indicate the presence of basement rocks on the continental shelf to the northeast of the Avalon Peninsula.

## Late Precambrian and Paleozoic Magmatism

Granitoid plutons are an important component of the eastern margin of the Appalachians. In the Avalon Zone of Newfoundland (Figure 5), two major episodes of plutonism are recognized (O'Brien *et al.*, 1983). The first, yielding isotopic ages mainly between 570 and 620 Ma, are hornblende–biotite granitoid rocks of the Holyrood Intrusive Suite (Figure 3), which were intruded during late Precambrian orogenesis. Chemical studies of the Newfoundland examples have shown them to be of calc-alkaline affinity (Strong and Minatides, 1975; O'Driscoll and Strong, 1979), chemically comparable with the granitoids in the Andean and western North American Cenozoic terrains, i.e., transitional between orogenic and non-orogenic environments.

The second plutonic episode, dated about 360 Ma, produced granites locally of batholithic proportions that were introduced during late stages of Acadian orogenesis (O'Brien *et al.*, 1983). These granites (Figure 5) were intruded into high crustal levels in the western Avalon Zone of Newfoundland and are locally mineralized (e.g., fluorite-bearing St. Lawrence Granite).

## Paleozoic Sedimentation

Remnants of a formerly widespread cover of platformal Cambro-Ordovician sedimentary rocks rich in Atlantic realm trilobites, and including minor associated volcanic rocks (Greenough and Papezik, 1985) overlies the Upper Proterozoic volcanic, sedimentary and granitoid rocks of eastern Avalon Peninsula (Figures 3 and 5). The basal Cambrian contact may be represented as an unconformity, nonconformity or disconformity. In the Manuels River area, to the southwest, an unconformity separates the base of the Cambro-Ordovician succession from underlying late Proterozoic volcanic rocks (Harbour Main Group) and granitoids (Holyrood Intrusive Suite). The oldest Cambrian sedimentary rocks are present in the southwestern part of the Avalon Zone of Newfoundland and are unrepresented on the Avalon Peninsula (e.g., Bengtson and Fletcher, 1983; Landing *et al.*, 1988).

Ordovician and Silurian marine siltstones and Devonian continental red sandstones have been obtained from submarine drill cores and dredge samples on the Grand Banks east of St. John's (King *et al.*, 1986; King, 1988). Silurian (?), Devonian and Carboniferous molasse-like sedimentary rocks also occur in the southwestern Avalon Zone of Newfoundland (Figure 5). These rocks unconformably overlie fossiliferous Upper Cambrian shales.

# STRUCTURAL GEOLOGY AND METAMORPHISM

## REGIONAL STRUCTURAL SETTING

Two periods of deformation have been identified in the eastern Avalon Peninsula: 1) an enigmatic Late Precambrian (Cadomian or Pan-African) orogenic episode, named the 'Avalonian' by Rodgers (1972) and first described as the 'Avalonian Orogeny' by Lilly (1966); and 2) a major Siluro-Devonian (ca. 395 Ma) disturbance—the 'Acadian Orogeny'.

The effects of the late Precambrian Avalonian Orogeny are enigmatic throughout the Avalon Zone of Newfoundland (Hughes, 1970). However, in the eastern Avalon Peninsula, the Avalonian appears to be relatively dominant. Unconformities in widespread localities throughout the Avalon Peninsula provide evidence of mainly late Precambrian folding, block-faulting, granitoid emplacement (620 Ma Holyrood Intrusive Suite) and general crustal instability (e.g., McCartney, 1967; Anderson *et al.*, 1975; Anderson, 1981; King, 1980, 1982). The present concentric arrangement of late Precambrian sedimentary rocks around a volcanic core in the eastern Avalon (Figure 3) appears to be the result of Precambrian structural doming, as Lower Cambrian strata overstep the Conception Group to lie directly upon the Holyrood granite and Harbour Main volcanics at Conception Bay (McCartney, 1967, 1969).

The effects of Acadian deformation and metamorphism in the Avalon Zone of Newfoundland are variable, reflecting the inhomogeneity of the Acadian event. In the western Avalon Zone of Newfoundland, it is represented by the unconformity of Devonian sediments on fossiliferous Upper Cambrian strata and is accompanied by folding, faulting, greenschist facies regional metamorphism and granitoid plutonism (e.g., O'Brien *et al.*, 1983). Metamorphism in the eastern Avalon Peninsula occurred under prehnite–pumpellyite facies conditions (Papezik, 1972b, 1974b). Neither the Avalonian nor the Acadian orogenic episodes within the map area are accompanied by extensive high-grade metamorphism or widespread penetrative fabric development.

## TECTONOSTRATIGRAPHIC ZONES

The Precambrian rocks of the St. John's area are open to tightly folded, depending upon their lithology and bed thickness. Broad elongate domes and basins with near vertical north-northeast trending, axial surfaces, and with associated doubly plunging parasitic folds are the dominant structural style (Figure 25). Axial planar cleavage varies around the vertical from steeply southeast to steeply northwest dipping.

The map area is divided into six tectonostratigraphic zones, each with its own distinctive rock types and structural styles (Figure 26). The principal distinguishing characteristics of the various formations and members are shown in the legend for Figure 7 and their vertical and lateral variations are summarized in Figure 6. A stratigraphic and structural profile is shown on the accompanying 1:25,000-scale map

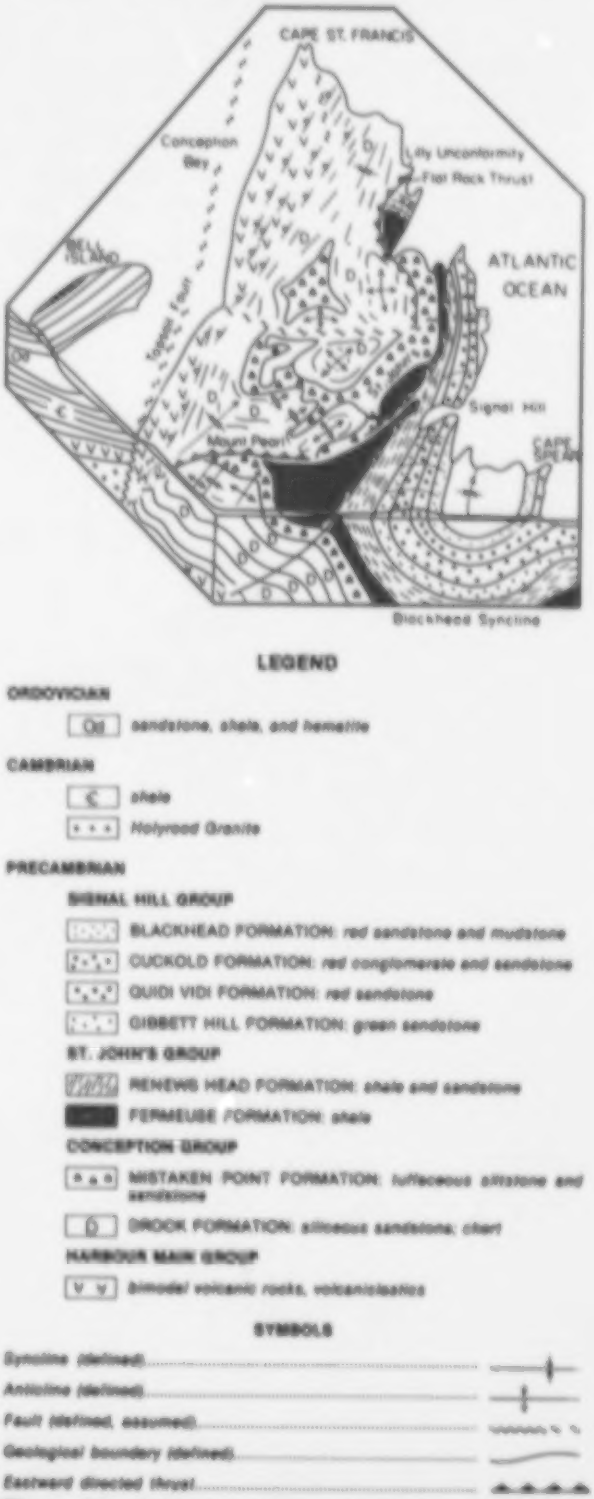

CAPE ST. FRANCIS
Conception Bay
Lilly Unconformity
Flat Rock Thrust
ATLANTIC OCEAN
BELL ISLAND
Topsail Fault
Signal Hill
Mount Pearl
CAPE SPEAR
Blackhead Syncline
LEGEND
ORDOVICIAN
Od sandstone, shale, and hematite
CAMBRIAN
€ shale
Holyrood Granite
PRECAMBRIAN
SIGNAL HILL GROUP
BLACKHEAD FORMATION: red sandstone and mudstone
CUCKOLD FORMATION: red conglomerate and sandstone
QUIDI VIDI FORMATION: red sandstone
GIBBETT HILL FORMATION: green sandstone
ST. JOHN'S GROUP
RENEWS HEAD FORMATION: shale and sandstone
FERMEUSE FORMATION: shale
CONCEPTION GROUP
MISTAKEN POINT FORMATION: tuffaceous siltstone and sandstone
D DROOK FORMATION: siliceous sandstone; chert
HARBOUR MAIN GROUP
V V bimodal volcanic rocks, volcaniclastics
SYMBOLS
Syncline (defined)
Anticline (defined)
Fault (defined, assumed)
Geological boundary (defined)
Eastward directed thrust

**Figure 25.** *Schematic diagram of the St. John's area showing formations and major structures.*

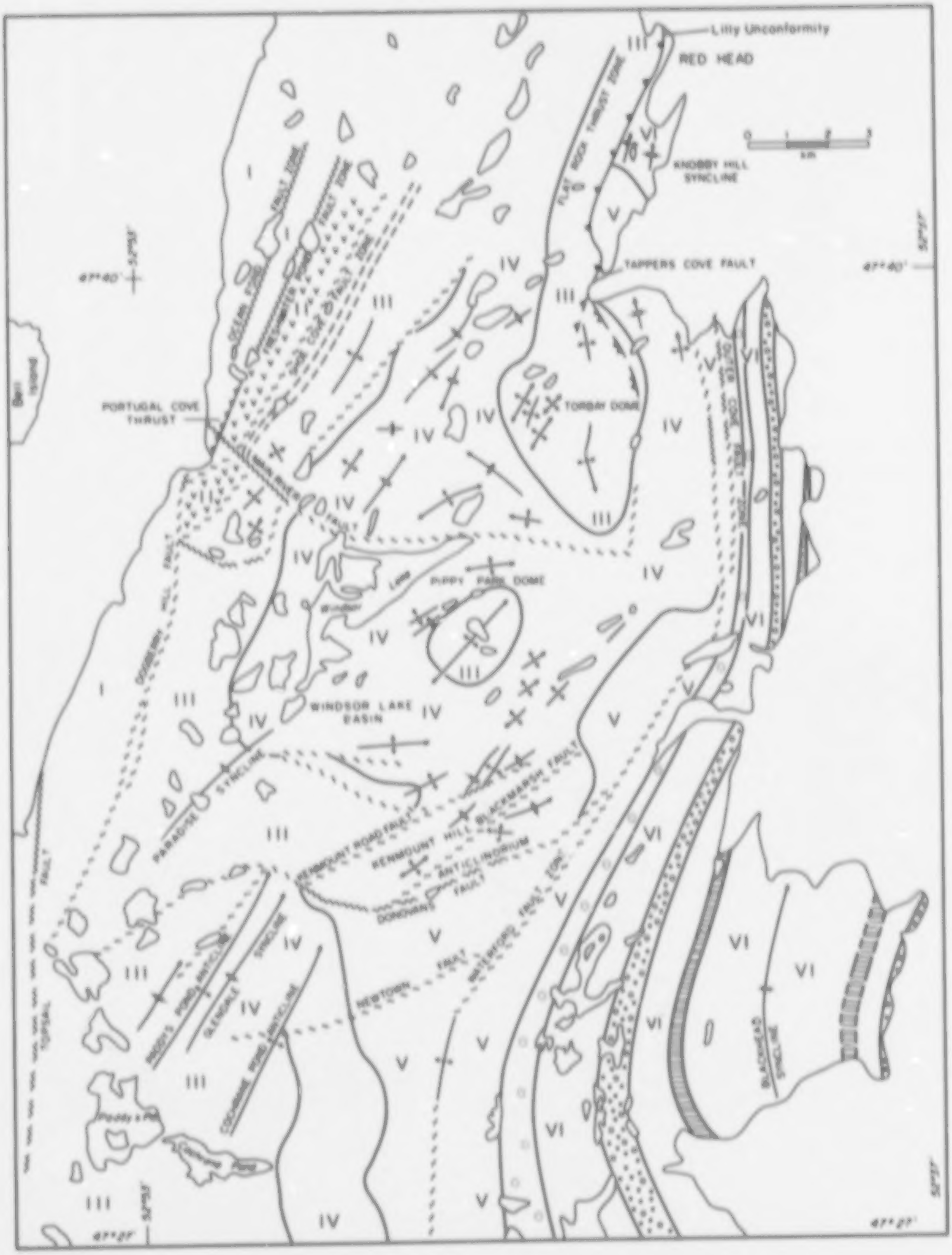

Lilly Unconformity
RED HEAD
FLAT ROCK THRUST ZONE
KNOBBY HILL SYNCLINE
TAPPERS COVE FAULT
TORBAY DOME
OUTER COVE FAULT ZONE
FAULT ZONE
PORTUGAL COVE THRUST
PIPPY PARK DOME
WINDSOR LAKE BASIN
GOOBERRY HILL FAULT
PARADISE SYNCLINE
KENMOUNT ROAD FAULT
KENMOUNT HILL ANTICLINORIUM
BLACKMARSH FAULT
DONOVANS FAULT
WATERFORD FAULT ZONE
NEWTOWN FAULT
GLENDALE SYNCLINE
PADDY'S POND ANTICLINE
COCHRANE POND ANTICLINE
TOPSAIL FAULT
BLACKHEAD SYNCLINE
47°40'
47°27'
52°37'
I
II
III
IV
V
VI

**Figure 26.** *Tectonostratigraphic zones of the St. John's area (see text for explanation).*

(Map 90-120). The characteristics of the zones are summarized below:

### Zone I: Topsail Head–Portugal Cove–Bauline

This zone, bounded by an eastern splay of the Topsail Fault (e.g., Plates 5 and 14), forms part of a complex, imbricate thrust stack and consists of highly deformed metatuffs (St. Phillips Formation), which are associated with strongly deformed siliceous sedimentary and mafic volcanic rocks (Portugal Cove Formation). Metapillow basalt and tuff (Blast Hole Ponds Unit, Princes Lookout Formation) and associated granitoid rocks are boudinaged. Weakly deformed stocks (Plate 7) and dykes of gabbro (Dogberry Hill) and felsite occur along the Dogberry Hill and Freshwater Pond faults, marking the eastern boundary of the zone.

### Zone II: Princes Lookout–Bauline Line area

This zone consists of fault-bounded blocks of massive and pillow basalt (Princes Lookout Formation). Red argillite beds in the basalt show open to tight folds; stratigraphic top determinations in the argillite and pillow basalts indicate much of the eastern margin of this zone, which is steeply dipping to the west, is overturned (Plate 12). A major shear zone, the Shoe Cove Fault, defines the eastern margin and is interpreted as a thrust fault.

### Zone III: Central St. John's

Both Zones I and II are in fault contact with Zone III, which is characterized by thick-bedded, greenish-grey chert and coarse grained siliceous volcaniclastic sandstone of the Drook Formation (e.g., Plate 20).

The members of the Drook Formation are relatively competent rocks, which form large-scale domes and basins corresponding with areas of topographic high and low relief. Windsor Lake for example, is within a complex structural basin (see accompanying section, 1:25,000 scale).

### Zone IV: Central to eastern St. John's

Zone IV is conformably above Zone III and is easily recognized by conspicuous red and green tuffaceous siltstones and sandstones of the Mistaken Point Formation. A distinctive marker unit of red, waterlain tuff and white, vitric tuff near the top of the Middle Cove Member has been traced throughout the central part of the map area, and defines the major structures within this zone (Figures 7, 10 and 11). Thin- to medium-bedded turbiditic argillaceous sandstone of the Trepassey Formation defines the top of the zone. The rocks in Zone IV are characterized by an intricate pattern of interference folds, particularly between the intervening domes of Zone III.

### Zone V: Tor Bay–Downtown St. John's–Mount Pearl–Goulds

Zone V, a coarsening-upward sequence, stratigraphically above and to the east of Zone IV, consists of tightly folded Fermeuse Formation black shale and Renews Head Formation sandy shale. Locally, Zone V pinches out, tectonically where squeezed between competent units or, where overthrust by competent units as in the Flat Rock Thrust zone.

### Zone VI: Eastern Flat Rock–Torbay Point–Petty Harbour–St. John's

This zone is comprised of competent units of Gibbett Hill Formation green sandstone (Plate 28), Quidi Vidi Formation red sandstone, Cuckold Formation conglomerate (Plate 30), Blackhead Formation sandstone and mudstone (Plate 36) and Flat Rock Cove Formation conglomerate, sandstone and breccia (Plate 41). These units, which comprise the Signal Hill Group, show lateral variations in thickness, composition, and texture.

Zone VI is, internally, the least deformed of the zones. Competent sandstones and conglomerates comprising this zone extend throughout eastern Avalon Peninsula and display broad, large-scale, open folds such as exemplified by the Blackhead Syncline (Figure 25).

## MAJOR TECTONIC ELEMENTS–DISCUSSION

The Precambrian rocks of the St. John's area provide evidence of progressive phases of deformation, generally most intense in the west and decreasing in intensity towards the east. The earliest phase is observable in Zones I, II and III (Figure 26) and is considered to have commenced during the Avalonian Orogeny; it is overprinted by younger Acadian episodes.

### Topsail Fault Zone

The Topsail Fault (Figure 3) extends along much of eastern Conception Bay, and separates Harbour Main volcanic rocks to the east from downthrown Cambro-Ordovician sediments to the west; it merges with the Frenchman's Cove Fault in southeastern Avalon Peninsula, where it is near vertical with its eastern side downthrown.

In the St. Phillips–Portugal Cove–Bauline area (Zones I, II, and III), the Precambrian rocks to the east of the Topsail Fault, in marked contrast with the Cambro-Ordovician rocks to the west, provide evidence of complex folding and faulting resulting from polyphase deformation. Preliminary fabric studies show that tectonically stretched tuff and rhyolite clasts define down-dip cleavage lineations, suggesting an early phase of tight-folding, rupture along axial surfaces and eastward directed thrusting. The northeast trending, high-angle Dogberry Hill, Portugal Cove, Ocean Pond, Freshwater Pond and Shoe Cove faults are possible conjugate splays of the

Topsail Fault and display components of high-angle eastward directed thrusting as well as subsequent strike-slip and oblique-slip motions. Preliminary studies indicate they all had a very long history and may relate to both Avalonian and Acadian orogenic episodes; fabrics within sheared tuffs, conglomerates, pegmatites and gabbros along or associated with these faults show that they were reactivated several times.

Minor cross-faults cut or terminate against the major faults and may be genetically related. The Main River Fault in the Portugal Cove–Windsor Lake area is a sinistral strike-slip fault with an oblique-slip component; pillowed and massive basaltic flows of the Princes Lookout Formation are clearly offset by this fault in the vicinity of Portugal Cove (Figure 7).

## Kenmount Hill Anticlinorium

The Kenmount Hill Anticlinorium (Zones III, IV and V) provides evidence of multiple progressive deformations. It is a complex horst-like block of tightly folded Drook strata; both early folds and associated faults within the block have been refolded or warped about a major northerly trending axis. It is possible that the younger open folds resulted from warping and southward decollement detachment of the block above a resistant basal unit, as may be provided by the Harbour Main volcanic rocks (Figure 27). Black shales of the St. John's Group exposed along Waterford River are separated from the block by the Donovans–Blackmarsh Fault; both tight folds in the shales and the Donovans Fault are warped around the southern end of the Kenmount Hill Anticlinorium. A steeply dipping, north-northwest-trending slaty cleavage is well developed in the Fermeuse Formation in the Mount Pearl area and is possibly a product of the younger folding phase.

The Donovans Fault trends parallel to the Waterford River in the Donovans–Mount Pearl area and is interpreted to splay into the Blackmarsh Fault northeast of Mount Pearl. Intense rock fracturing, brecciation and massive quartz veining were noted along faults in numerous water and sewer line excavations made for the Cowan Heights development; the Trepassey Formation in this area is highly fractured. The fault trace at Donovans and throughout most of its length is marked by structural discontinuity, with its southern side downthrown; at Donovans, for example, streaky sandstone (facies B-4c) of the Torbay Member is juxtaposed against black shale of the Fermeuse Formation to the south.

The northeast trending Kenmount Road Fault is a minor fault zone that defines the northern margin of the Kenmount Hill Anticlinorium. Closely spaced and steeply northwest dipping faults are exposed at several localities along its length. It is interpreted as a minor pivotal fault with the north side downthrown. Slickensides and rock plucking along the fault surface indicate normal or down-dip movement; the amount of strike-slip displacement is uncertain.

## Lilly Unconformity

In the Lilly Unconformity at Red Head (Figure 21), easterly dipping red breccia beds (Piccos Brook Member) unconformably overlie thin-bedded folded siliceous sandstones (Drook Formation). This is the only known place in the eastern Avalon where a major hiatus has developed within the late Precambrian sequence; tectonic deformation of considerable magnitude (Avalonian Orogeny) took place at this locality (Anderson *et al.*, 1975). The St. John's shale slice of the Flat Rock Thrust Zone is in tectonic contact with both the red breccia and the Conception sandstones beneath it. Specimens of the Vendian microfossil *Bavlinella*, were found in the shales by A.H. Knoll (Hofmann *et al.*, 1979). Subsequent folding of the unconformity, possibly during the Acadian orogeny, produced the Red Head Syncline (Figure 18), which may be genetically related to the Flat Rock thrusting.

## Flat Rock Thrust Zone

The east to east-northeast directed Flat Rock Thrust Zone extends from Red Head to southwestern Torbay Bight and along the eastern margin of the Torbay Dome. A low-angle thrust fault between Small Point (2 km north of Red Head) and Black Head North may represent a northern extension of the zone (Figure 1).

Between Flat Rock Cove and Red Head, lozenge-shaped, highly fractured black shales of the St. John's Group were thrust over red beds of the Piccos Brook Member (Figures 18 to 21). As there are no intervening black shales below the Lilly Unconformity, a minimum dextral strike-slip component of at least 3 km or a dip-slip component of at least 5 km was required to transport the shales to their present position.

Between Red Head and Tappers Cove (Torbay Bight), the main leading edge of the Flat Rock Thrust Zone consists of westward dipping beds of the Torbay, Bauline Line and Broad Cove River members. At Gallows Cove Ponds, mixtite of the Bauline Line Member is juxtaposed against highly cleaved shales of the Fermeuse Formation to the east (Figure 18). Small splays are present in the Torbay Road–Gallows Cove Pond Road intersection, and from there the fault zone continues southward in an arcuate fashion via Tappers Cove to Torbay Bight where Mistaken Point Formation rocks are thrust over black shales of the Fermeuse Formation (Figure 10).

On the eastern side of Tappers Cove, streaky sandstones of the Torbay Member are in fault contact with red beds of the Mistaken Point Formation (Figure 10). A northwest trending dextral cross-fault in Tappers Cove gulch (the Tappers Cove Fault) offsets the main zone, which continues along the southwestern side of Torbay Bight. Cull (1968) sketched the tight chevron-folds, well exposed along the southeastern shore of Torbay Bight, and was the first to propose that this section had been overthrust by older Conception Group strata; he suggested that the present land surface between Torbay Bight

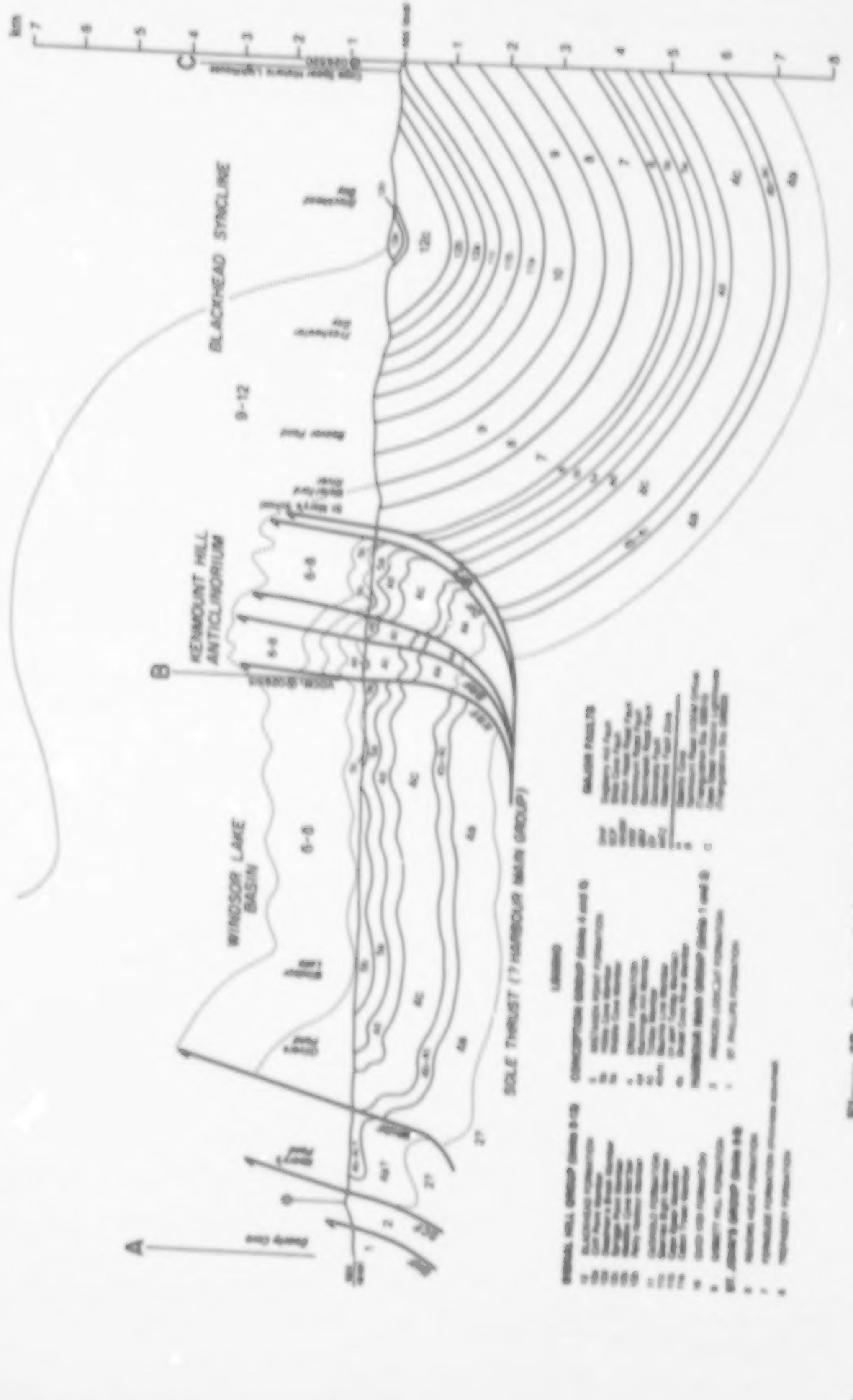

A
B
C
km
WINDSOR LAKE BASIN
KENMOUNT HILL ANTICLINORIUM
BLACKHEAD SYNCLINE
SOLE THRUST (? HARBOUR MAIN GROUP)
9-12
5-8
LEGEND

*Figure 27. Structural alignment along the Beachy Cove (A)—Kenmount Hill (B)—Cape Spear (C) transect.*

and Middle Cove is close to that of the now eroded hangingwall. Present studies support this interpretation with respect to the southwestern Torbay Bight area (Figure 10).

The Flat Rock Thrust Zone continues south of Torbay but is presently impossible to trace because of drift cover. Its leading edge may coincide with the thick bedded, mildly deformed sandstones (Torbay Member) in the eastern part of the Torbay Dome, which are juxtaposed against tightly folded and ruptured beds of the Mistaken Point Formation. It may also link with an easterly trending shear zone, the Wedgewood Park Fault. Site excavations in the vicinity of Highland Drive (Wedgewood Park and Woodlands), show highly contorted, sheared and brecciated bedrock with fractures lined with quartz veins (up to 0.5 m thick).

It seems probable that the Torbay and Pippy Park domes, together with the Kenmount Hill Anticlinorium were structurally transported to the east along a series of thrust and associated strike-slip faults (Figure 25). Much of the deformation in tectonostratigraphic zones 4 and 5 is thought to relate to these motions. It seems probable that the Flat Rock Thrust Zone and the Donovans Fault are genetically related but their merger is somewhat speculative.

### Waterford Fault Zone

An arcuate, highly deformed and disrupted zone of shearing and thrusting extends from the Outer Cove–Middle Cove area via Virginia Lake to downtown St. John's (City Hall area), and then along the Waterford River valley to the Goulds. It consists of a north-northeast-trending, 100- to 1000-m-wide zone of tightly folded, faulted and disrupted strata of the Fermeuse Formations (Figure 27). This zone, here named the Waterford Fault Zone, resulted from intense compression of mainly incompetent shales between relatively competent sandstones within the Kenmount Hill Anticlinorium, the Pippy Park and Torbay domes and the Blackhead Syncline. Spectacular minor folds are exhibited along the gorge of South Brook, especially where the Pitts Memorial Drive crosses the South Brook River near Bowring Park.

### Eastern Deformed Belt

Continued compression produced major open folds with steep axial surfaces and coplanar cleavage. Examples are the gently northward plunging Paddys Pond and Cochrane Pond anticlines and the Glendale and Blackhead synclines (Figure 7). These plunging structures are important conduits for groundwater movement and the synclines are potential aquifers.

The headwaters of South Brook follow a low, generally eastward trending valley, which crosses the Cochrane Pond Anticline. Although there is little rock exposure, the axis of the Cochrane Pond Anticline appears on aerial photographs to be offset, suggesting the presence of a minor strike-slip fault, referred to here as the Newtown Fault. It extends almost to the Trans-Canada Highway, where it appears to originate as a bedding plane fault; to the east of the Pitts Memorial Drive–Ruby Line intersection, it passes into the Waterford Fault Zone.

The Blackhead Syncline is a major fold on the eastern side of the map area (Figures 25, 26, 27). Bedding attitudes and thicknesses show that this fold is asymmetrical and is plunging 5 to 8° north-northeast. The base of the Blackhead Formation is estimated to be about 1600 m b.s.l., at Cliff Point. The formation is about 1700 m thick on the west limb of the syncline, between Freshwater Bay and Cliff Point and about 1500 m thick on the east limb between Cliff Point and Spear Bay.

## MINOR TECTONIC ELEMENTS

Numerous joint sets and fracture zones are evident in virtually all rock units present in the map area. Joint systems are especially well developed in thick bedded sandstones and conglomerates of the Signal Hill Group.

Rhombohedral joints are characteristic of the Signal Hill Group and probably developed perpendicular to the stratification during the early stages of folding. One low-angle penetrative joint set (dip 15 to 35°N), particularly well developed in the Gibbett Hill Formation, is commonly filled with white quartz, minor pale-green prehnite, and traces of calcite, pyrite and pyrolusite. This set can be traced from Petty Harbour to Torbay Point. Some joint sets contain amethyst and copper minerals (O'Driscoll and King, 1985).

Irregular or curviplanar fractures are commonly parallel to axial surfaces in tightly folded rocks and are associated with fault zones and splays. It is noteworthy that one of the first attempts at mining in Newfoundland, was made in 1778 on a small, quartz–calcite–bornite vein in Signal Hill sandstone at Shoal Bay (Rose, 1952).

## METAMORPHISM

The Late Precambrian rocks of the Avalon Peninsula have undergone low-grade metamorphism of the prehnite–pumpellyite facies (Papezik, 1972b, 1974b). Prehnite has been identified in veins, amygdule fillings and interstitial patches at several localities between Gibbett Hill and the western shore of Conception Bay; pumpellyite appears to be confined to the volcanic rocks around Conception Bay (Papezik, 1974b). This facies, intermediate between the zeolite and the greenschist facies, is commonly considered to be the result of a relatively deep burial of the sediments; Papezik (1972b) suggested a depth of about 4.5 km. Papezik's (1972b) studies showed that the local mottling of the thick, grey sandstones of the Gibbett Hill Formation is due to diffuse patches of interstitial prehnite, a typical feature of laumontitized sandstone.

Pumpellyite has not been identified so far in the Gibbett Hill Formation, perhaps an indication that the somewhat higher temperatures necessary for its formation have not been reached. Metamorphism within the western Avalon Zone occurred under prehnite–pumpellyite to mid-greenschist facies conditions. The intensity of the Acadian tectonothermal event is greatest adjacent to the Dover–Hermitage Bay Fault (Blackwood and Kennedy, 1975).

# TECTONIC MODELS

## Synopsis

Since the pioneering studies of Buddington (1919), a variety of tectonic models have been proposed for the Late Precambrian development of the Avalon Peninsula and the Avalon Zone of Newfoundland. McCartney (1969) proposed a model that would permit sequential development of the sedimentary units on the Avalon Peninsula in response to Precambrian tectonism. Evidence for such deformation has been cited by Lilly (1966), McCartney *et al.*, (1966) and Poole (1967) and this gave rise to the view that the intrusion of the Holyrood granite took place during an 'Avalonian Orogeny', which post-dated the Harbour Main volcanism and pre-dated the deposition of the Conception Group sediments. McCartney (1969) suggested that a north–south trending horst developed in volcanic and other rocks in the central part of the Avalon Peninsula and that arkosic detritus was shed to basins on either side to form the 'Hodgewater and Cabot groups' respectively. Each of the two groups is now known to contain the St. John's and Signal Hill groups.

In previous accounts of the Avalon Zone, two contrasting tectonic models have emerged. One depicts the 'Avalonian' terranes as having formed in an ensialic rift setting (e.g., Papezik, 1970; Strong *et al.*, 1978). The second model utilizes a consuming plate margin or ensialic island-arc concept (e.g., Hughes and Brückner, 1971; Rast *et al.*, 1976; Skehan and Murray, 1980; Rast, 1980) to model the Late Proterozoic evolution of the zone.

A consequence of the *rifting* model is that it has led to the concept of the Avalon Zone as a precursor stage to the opening of Iapetus and, therefore, the implication of a genetic relationship with the Appalachian orogen (e.g., Papezik, 1970; Williams *et al.*, 1972). The Late Precambrian age and bimodal nature of many of the Avalon Zone volcanics, coupled with the continuity of the zone along the eastern margin of the Appalachian Orogen supports this model. However, the model does not adequately explain either the absence of the Avalon Zone in the Scandinavian Caledonides or its apparent continuity with the Pan-African terranes of North Africa and Europe (Figure 28). While this model is compatible in some aspects with the Late Precambrian volcano-sedimentary facies of the zone, it is not applicable to its earlier facies development (O'Brien *et al.*, 1983).

The tectonic significance of the Avalon Zone and its extensions in any plate tectonic model for the Caledonian–Appalachian Orogen of the North Atlantic region is at present poorly understood. The main points of a tectonic model for the Proterozoic evolution of the Canadian Avalon Zone proposed by O'Brien *et al.*, (1983) and relevant to the area under discussion are as follows.

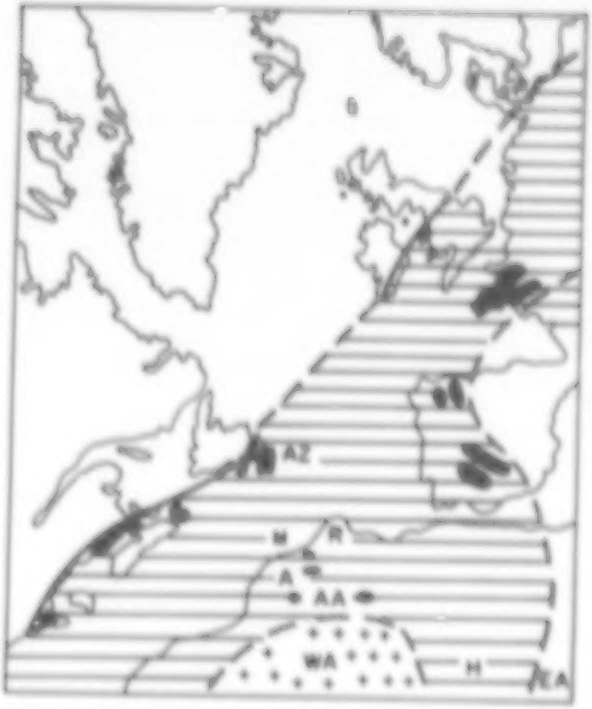


**Figure 28.** *Distribution of Avalonian–Cadomian–Pan-African terranes in the North Atlantic borderlands (Pre-Mesozoic reconstruction). Az = Avalon Zone, R = Rif, M = Meseta, A = High Atlas, AA = Anti-Atlas, WA = West African Craton, H = Hoggar, EA = East African Craton (King and O'Brien, in press).*

The evolution of the Zone began sometime between 1000 and 800 Ma with initial attempts to rift a pre-Pan-African, Avalonian continental basement. Rifting was followed by closure of the locally developed ocean basins, local and limited subduction, and collision associated with crustal melting to produce the Upper Proterozoic volcanic assemblages (e.g., Harbour Main Group). This stage of orogenesis terminated with intrusion of late granites (e.g., Holyrood Intrusive Suite), block faulting, and marine to terrestrial clastic deposition with local volcanicity. Widespread turbiditic and pelagic sedimentation (e.g., Conception Group) coincided with waning volcanism. A southward prograding delta marked initial shoaling of the marine basin (e.g., St. John's Group). Early mud and sand deposition gave way to sands and gravels derived from a mountain front on the northern periphery of the system (e.g., Signal Hill Group). The latest Proterozoic–Early Paleozoic was marked by peneplanation and transgression by the Cambrian sea and subsequent Cambro-Ordovician sedimentation.

In conclusion, the geological history of St. John's is part of a larger, Precambrian–earliest Paleozoic, Pan-African event. The rocks forming this original landmass were juxtaposed with the remainder of the Appalachian orogen during or after closure of the Paleozoic Iapetus Ocean (e.g., Cocks and Fortey, 1982). The overall similarity in the stratigraphic development, faunal assemblages and tectonics of the Avalon Zone, the Anti–Atlas of Morocco and other Pan-African belts of Northwest Africa (e.g., Martin and Porada, 1977) implies that they evolved in similar tectonic environments (O'Brien *et al.*, 1983; Pique *et al.*, 1990).

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# APPENDIX 1

## Grain-Size Scales for Sediments

The scale most commonly used for sediments is the Wentworth (1922) scale. The (phi) scale, devised by Krumbein (1941), is equal to the negative logarithm to the base 2 of the size in mm (e.g., 1 mm = 0Φ, 2 mm = −1Φ, 4 mm = −2Φ).

| Millimeters mm | Microns | Phi units (Φ) | Wentworth Size Class |
|---|---|---|---|
| 256 | | -8 | Boulder (-8 to -12Φ) |
| 128 | | -7 | Large cobbles |
| 64 | | -6 | Small cobbles |
| 32 | | -5 | Very large pebbles |
| 16 | | -4 | Large pebbles |
| 8 | | -3 | Medium pebbles |
| 4 | | -2 | Small pebbles |
| 2.00 | 2000 | -1.0 | Granule |
| 1.00 | 1000 | 0.0 | Very coarse sand |
| 0.50 | 500 | 1.0 | Coarse sand |
| 0.25 | 250 | 2.0 | Medium sand |
| 0.125 | 125 | 3.0 | Medium sand |
| 0.0625 | 62.5 | 4.0 | Very fine sand |
| 0.0312 | 31.2 | 5.0 | Coarse silt |
| 0.0156 | 15.6 | 6.0 | Medium silt |
| 0.0078 | 7.8 | 7.0 | Fine silt |
| 0.0039 | 3.9 | 8.0 | Very fine silt |
| 0.0020 | 2.0 | 9.0 | Clay (8Φ and higher) |

# APPENDIX 2

## Granulometric Classification of Pyroclastic and Epiclastic Deposits (after Schmid, 1981)

| AVERAGE CLAST SIZE (mm) | PYROCLASTIC DEPOSIT | TUFFITES (MIXED −EPICLASTICS) |
|---|---|---|
| 64 | Agglomerate,<br>Pyroclastic breccia | Tuffaceous conglomerate |
| 2 | Lapilli-tuff (lappilistone) | Tuffaceous breccia |
| 0.0625 | Coarse (ash) tuff | Tuffaceous sandstone |
| 0.0039 | Fine ash tuff | Tuffaceous siltstone<br>Tuffaceous mudstone, Shale |

# APPENDIX 3

## Bedding Thickness Terms (after Ingram, 1954)

| Name | Thickness |
|---|---|
| Extremely thick bedded | > 3 m |
| Very thick bedded | 1-3 m |
| Thick bedded | 30-100 cm |
| Medium bedded | 10-30 cm |
| Thin bedded | 3-10 cm |
| Very thin bedded | 1-3 cm |
| Thickly laminated | 0.3-1 cm |
| Thinly laminated | < 0.3 cm |

MAPS
NOT
FILMED

CARTES
OMISES